

Trapping and Probing Antihydrogen

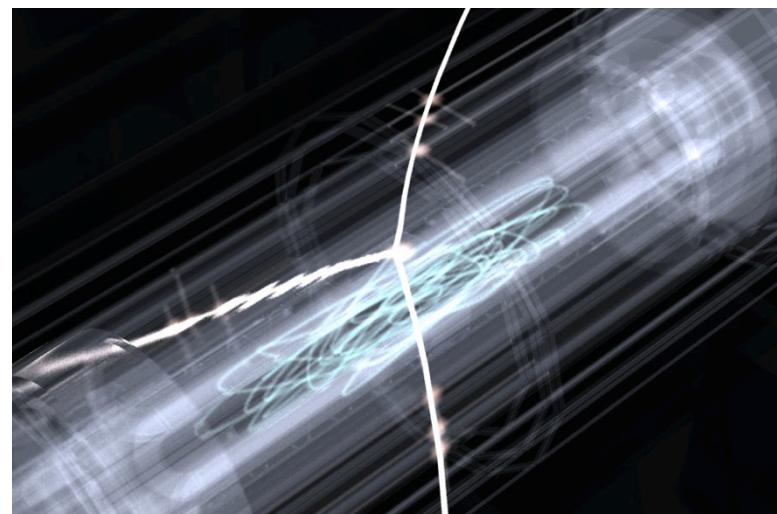
Jonathan Wurtele
U.C. Berkeley and LBNL
FNAL Colloquium
March 27, 2013



The ALPHA Collaboration

G.B. Andresen, M.D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P.D. Bowe, E. Butler, C.L. Cesar, S. Chapman, M. Charlton, A. Deller, S. Eriksson, J. Fajans, T. Friesen, M.C. Fujiwara, D.R. Gill, A. Gutierrez, J.S. Hangst, W.N. Hardy, R.S. Hayano, M.E. Hayden, A.J. Humphries, R. Hydomako, S. Jonsel, L. Kurchaninov, N. Madsen, S. Menary, P. Nolan, K. Olchanski, A. Olin, A. Povilus, P. Pusa, F. Robicheaux, E. Sarid, D.M. Silveira, C. So, R.I. Thompson, D.P. van der Werf, J. S. Wurtele, Y. Yamazaki and A. Zhmoginov

16 Institutions, ~40 researchers



F, LBNL

Antiparticles

1928-1931 - Dirac: Existence of the positron.



P. Dirac



P. Dirac

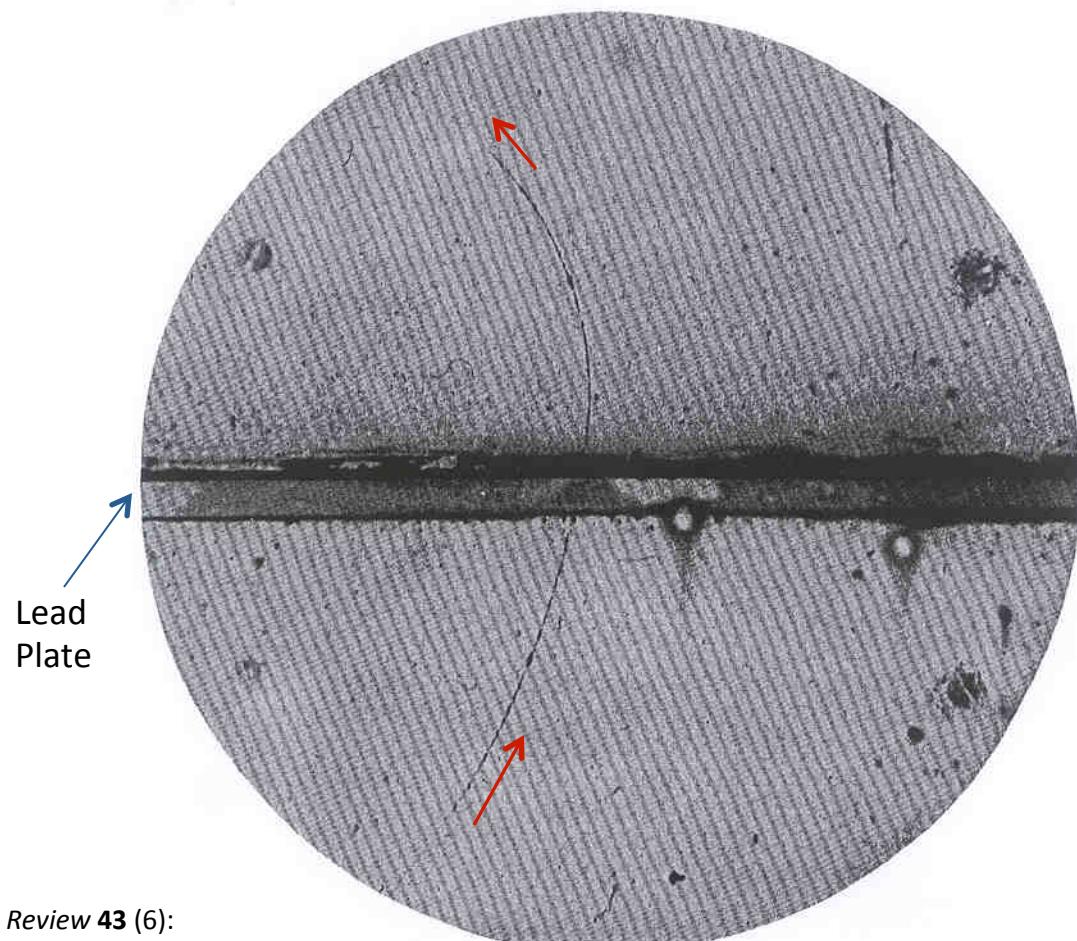
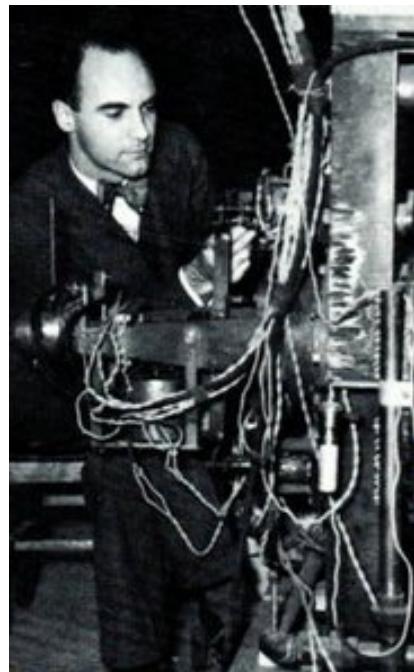
"A hole, if there were one, would be a new kind of particle, unknown to experimental physics, having the same mass and opposite charge to an electron. We may call such a particle an anti-electron."

P. A. M. Dirac, Quantised Singularities in the Electromagnetic Field, Proc. R. Soc. Lond. A **133** p60 (1931).

Positrons

1928 - Dirac: Existence of the positron.

1932 - Anderson : Discovered positrons in Cosmic rays.



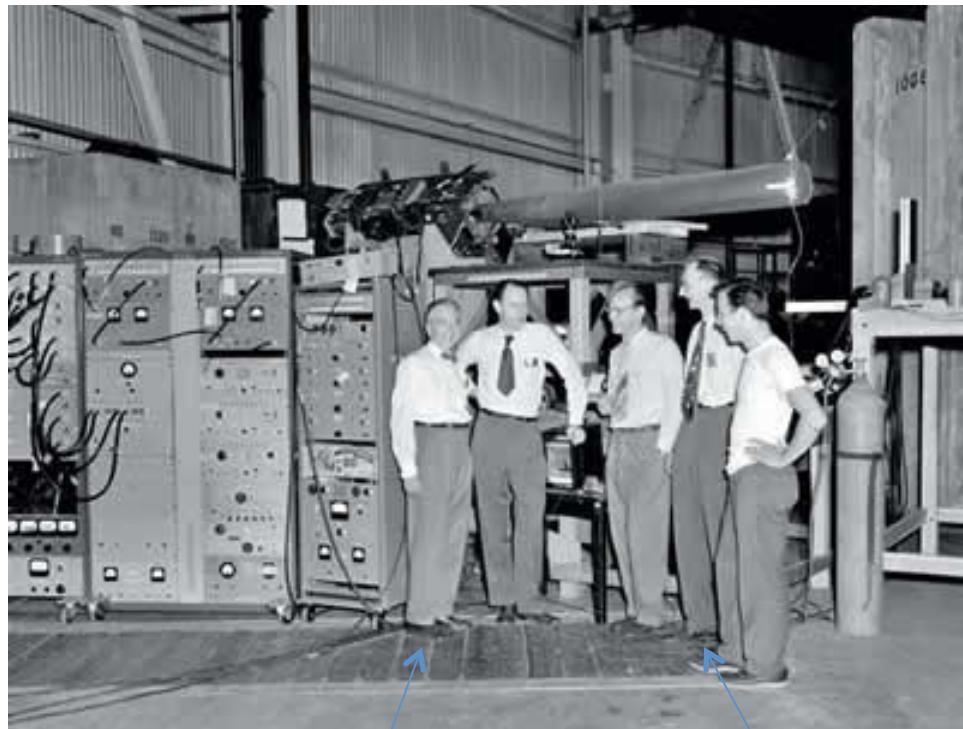
Anderson, Carl D. (1933). "The Positive Electron". *Physical Review* **43** (6):
491–494

Antiparticles

1928 - Dirac : Relativistic quantum mechanics

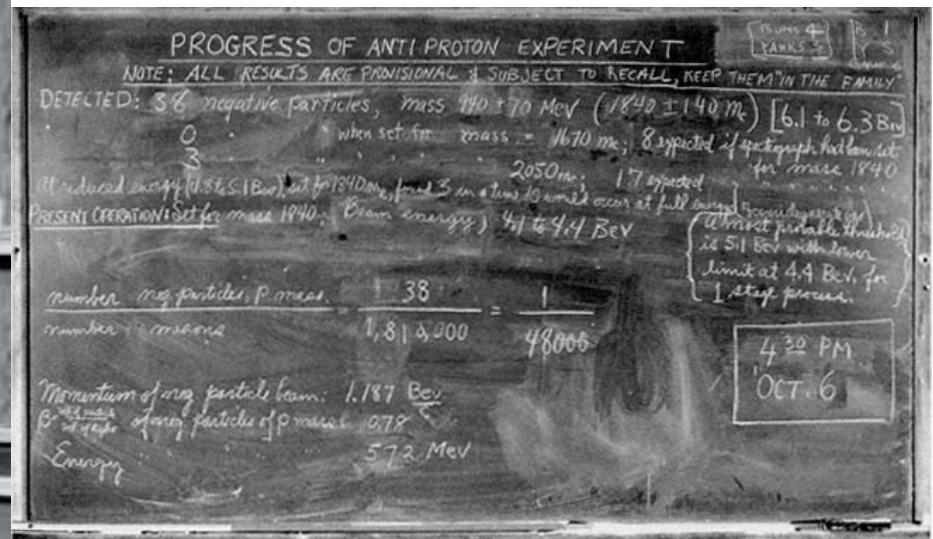
1932 - Anderson : Positron discovery.

1955 – Segre and Chamberlain: Antiproton discovery at the Bevatron in Berkeley.



Chamberlain

Segre

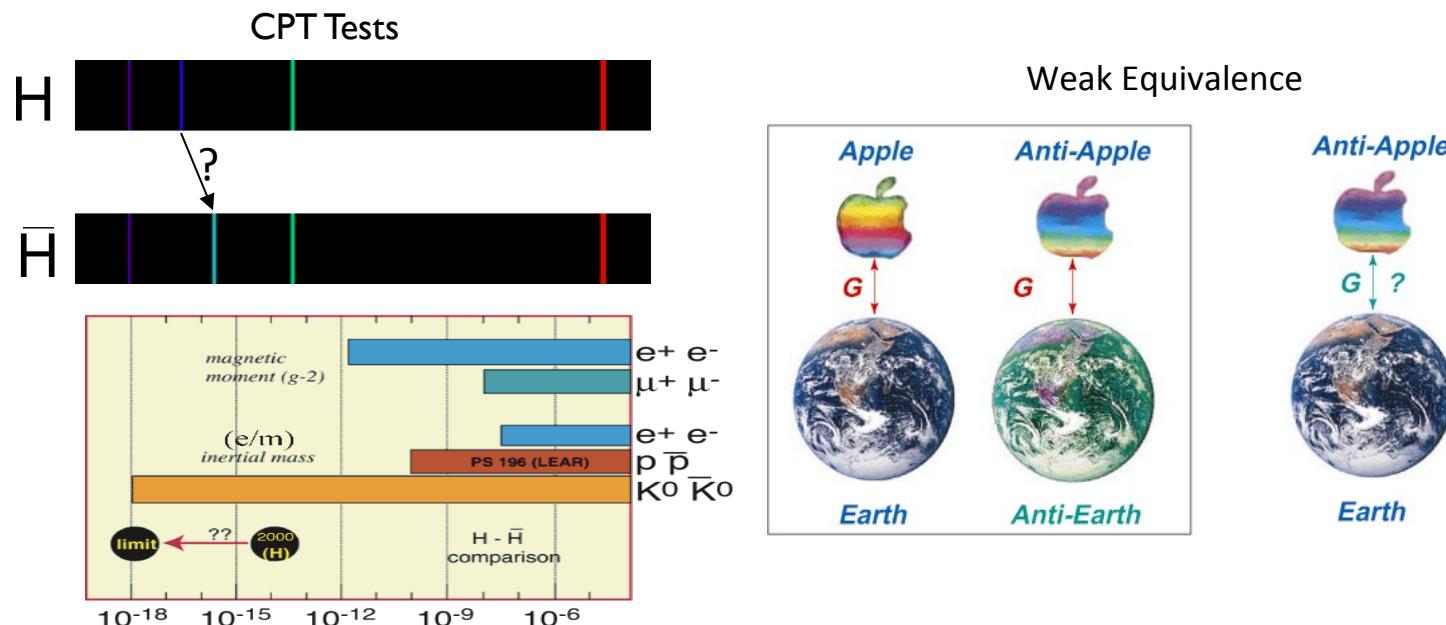


World Wide Web circa 1955

O. Chamberlain, E. Segrè, C. Wiegand, and T. Ypsilantis, Observations of antiprotons. Phys. Rev. **100**, p947 (1955).

Why Study Antihydrogen?

- The universe almost entirely of matter. **Why?**
- CPT Theorem: Physical laws identical under CPT transformations. Exceptions?
 - 1s-2s spectral comparison of hydrogen and antihydrogen.
- Gravity and Antimatter: Weak equivalence principle.
 - Highly speculative: do antiprotons fall upwards?



The Early History of Antihydrogen

- Nine antihydrogen atoms made at LEAR (1996)
- Ninety-nine more made at Fermi Lab. (E862; PRL 99)
- 2GeV/c energy-- antihydrogen not very useful.

CERN builds the AD for antimatter physics in the late 1990's.

Soon after: ATHENA creates cold untrapped antihydrogen 2002
ATRAP creates cold untrapped antihydrogen 2002

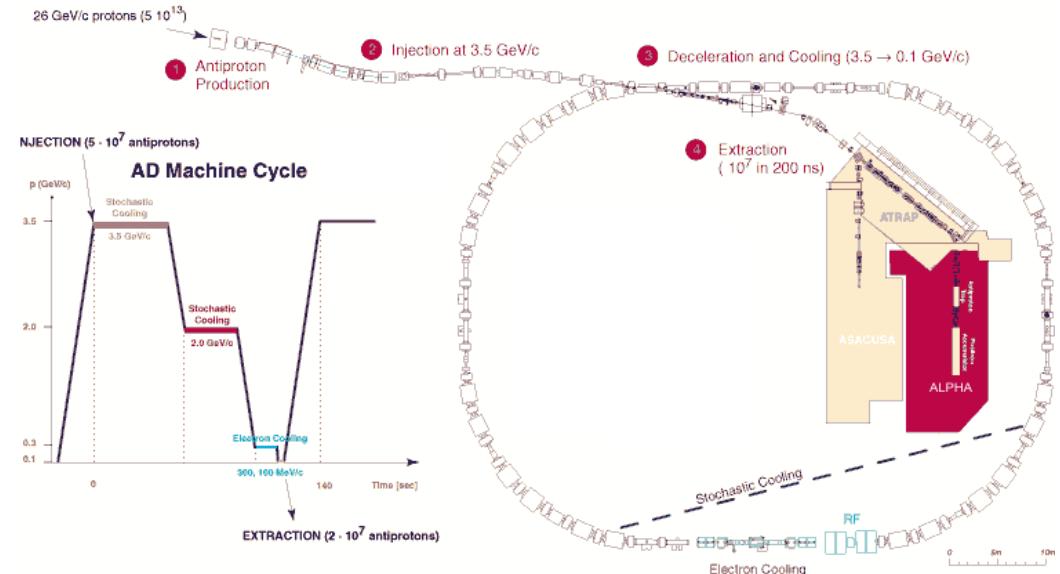
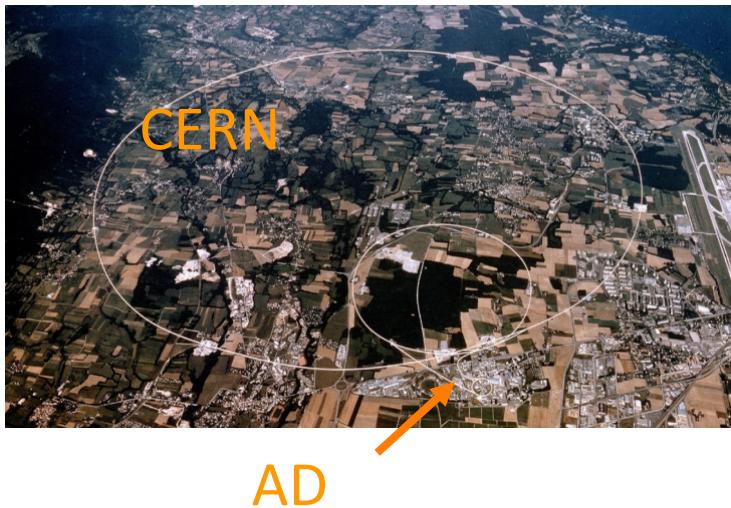
M. Amoretti, et al. (ATHENA), Production and detection of cold antihydrogen atoms, Nature 419, 456 (2002).

G. Gabrielse, et al., Background-free observation of cold antihydrogen with field-ionization analysis of its states, Phys. Rev. Lett. 89, 213401 (2002).

- Spectral and gravity measurements with ALPHA require cold, trapped antihydrogen. This talk describes
 1. How trapped antihydrogen was accomplished
 2. Resonant microwave manipulations of antihydrogen
 3. First application of a new technique to measure the gravitational mass of antihydrogen

Cold (100-1000K) Antihydrogen

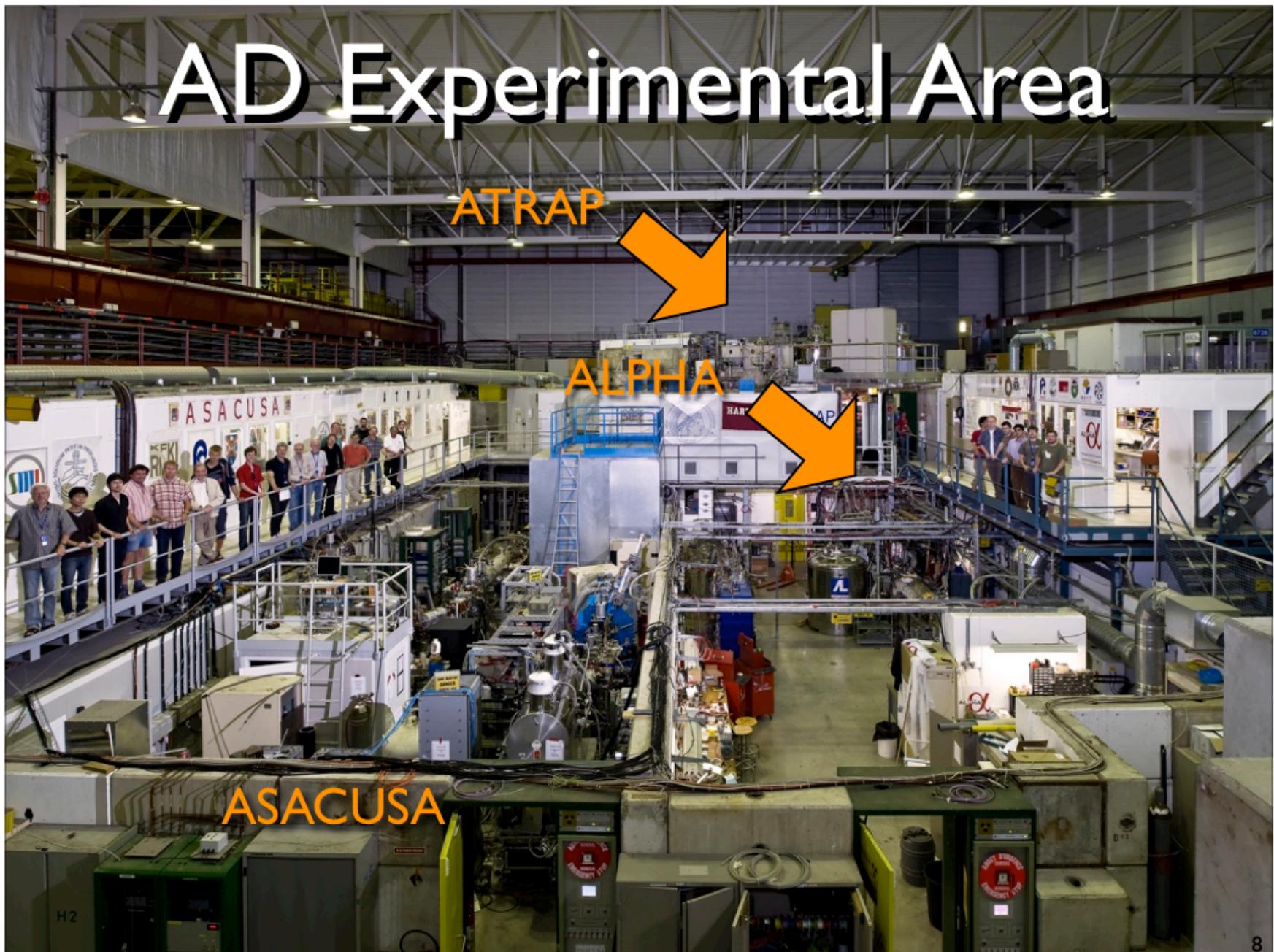
- First made at CERN by ATHENA and ATRAP in 2002.
- Hundreds of millions of antiatoms made.

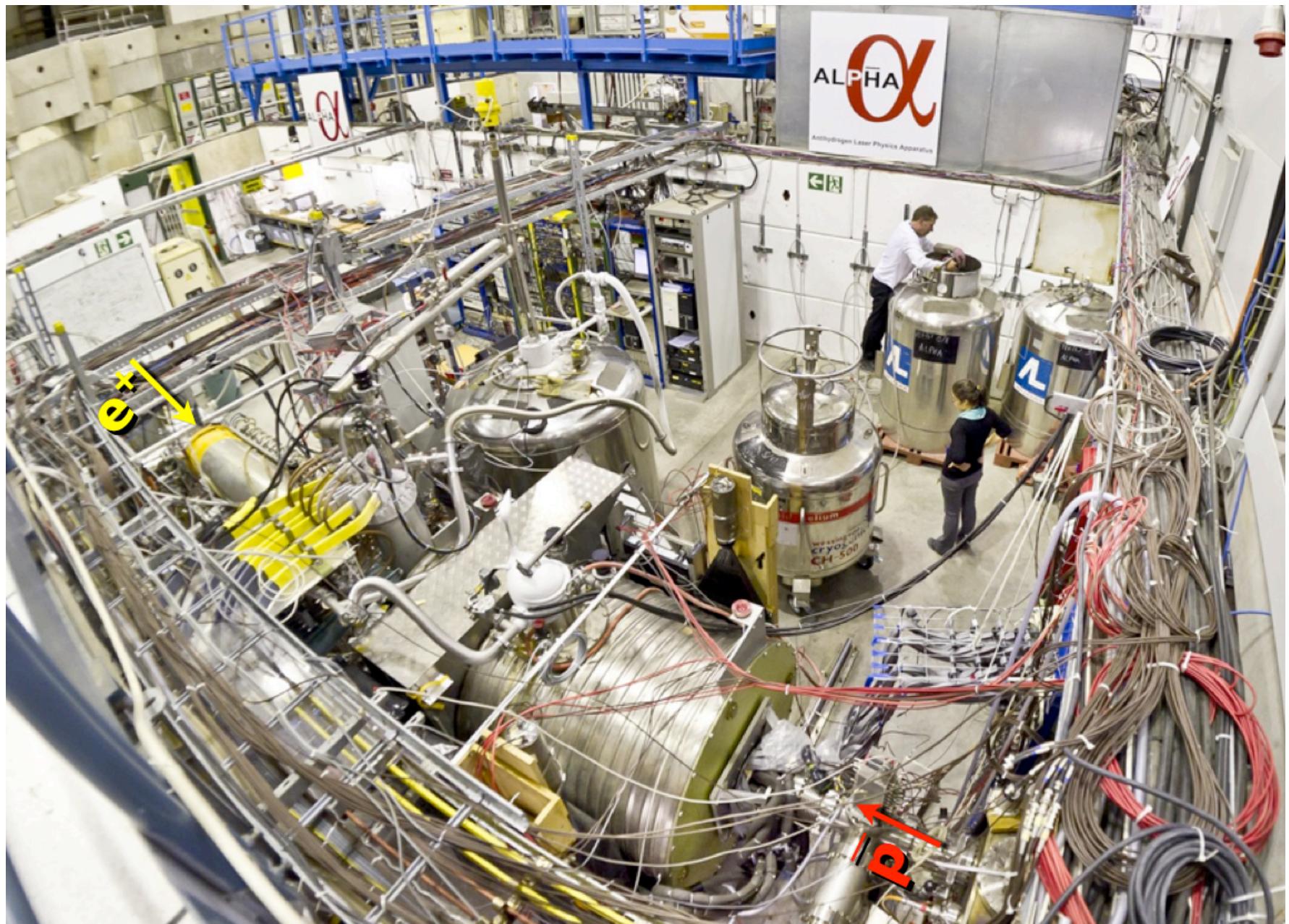


Antiproton Deaccelerator

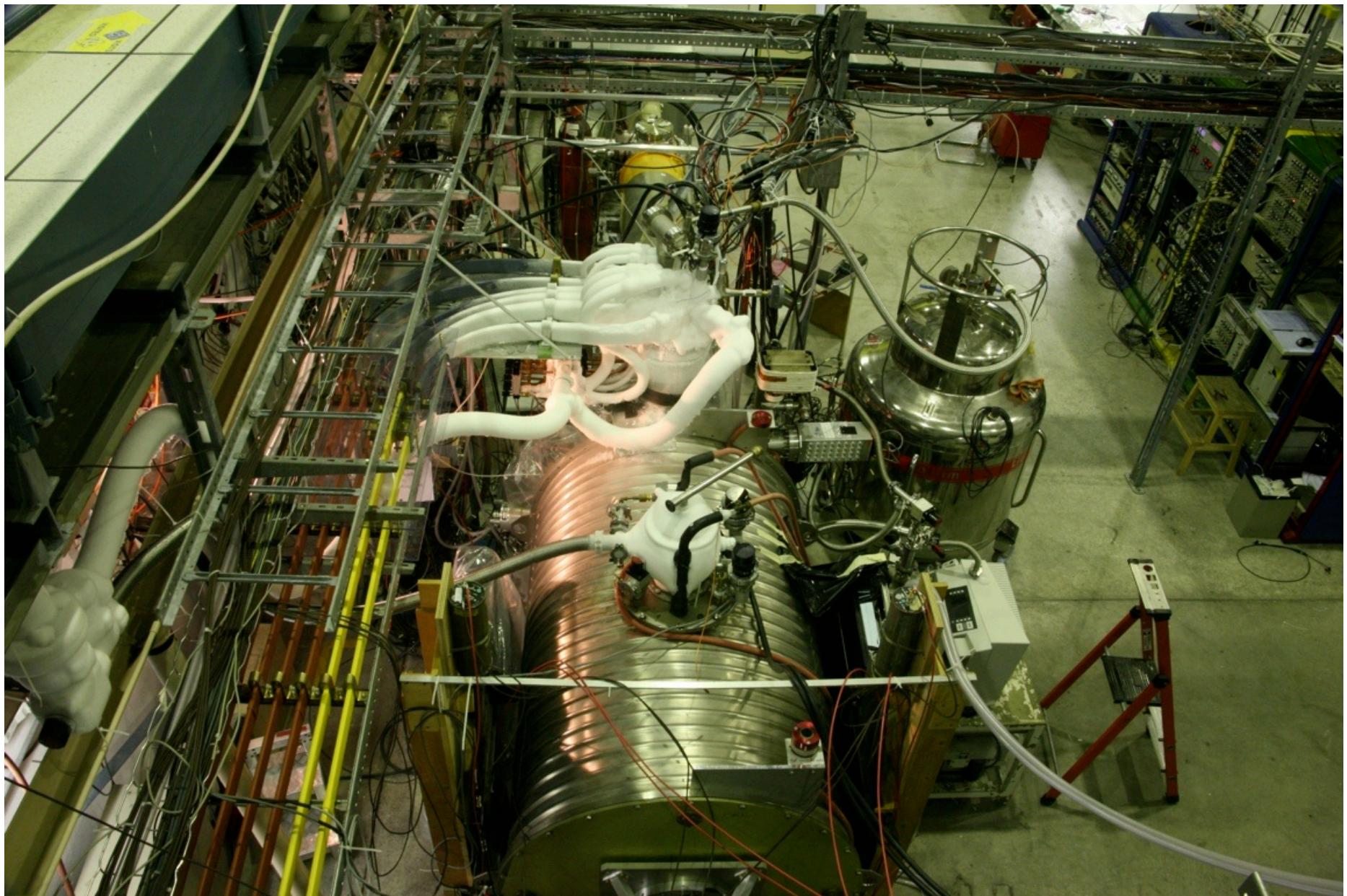
- CERN's Antiproton Deaccelerator reduces antiproton energy to ~ 5 MeV.

AD Experimental Area

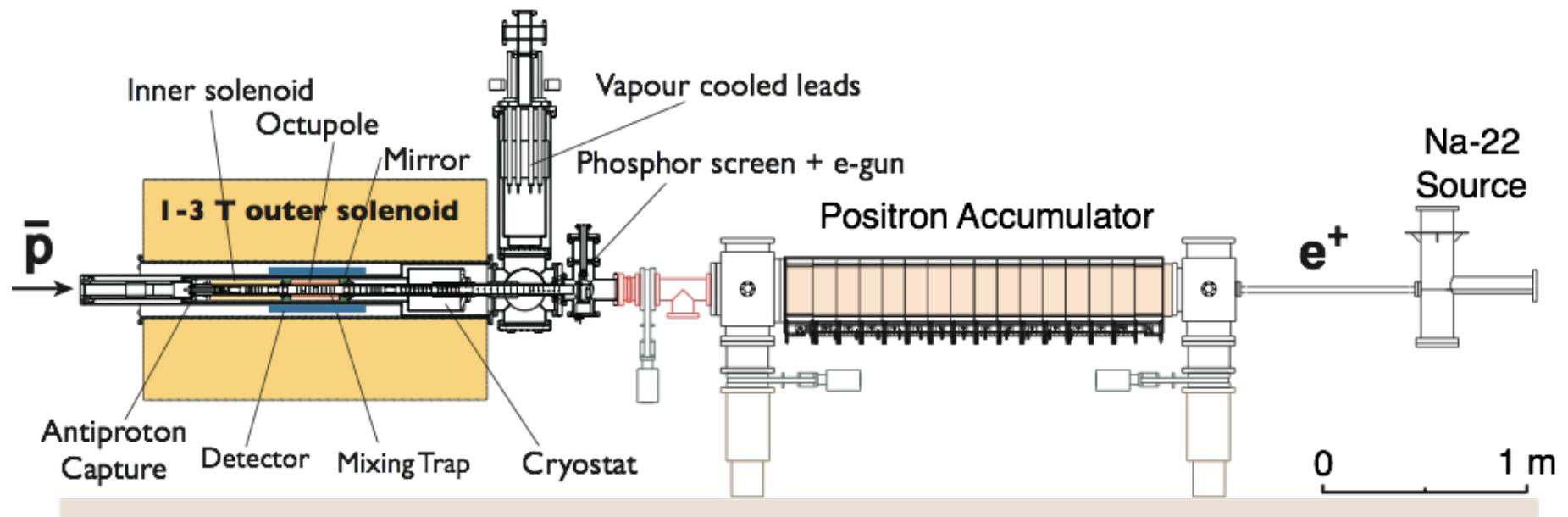




Alpha Apparatus



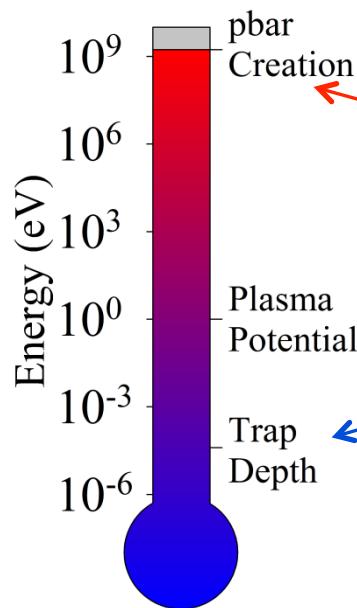
ALPHA Apparatus



ATRAP apparatus broadly similar.



Antihydrogen Production Energy Scales



Energy Scales:

Antiproton Creation Energy: 1.7GeV

Self-Potential: 30mV-10V

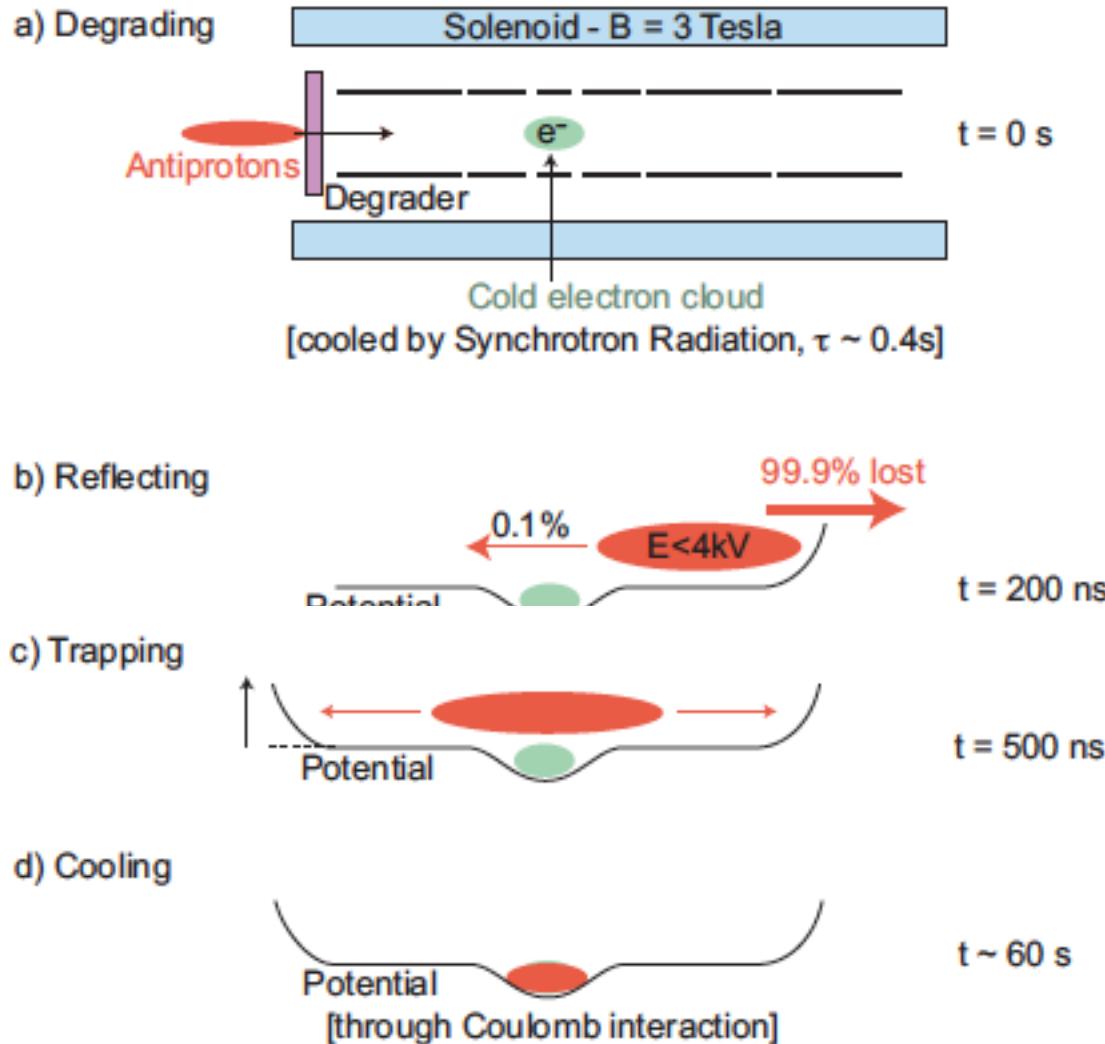
Trap Depth: 0.5K or 40 μ eV

$$\frac{\text{Antiproton Creation Energy}}{\text{Trap Depth}} = 10^{14}$$

$$\frac{\text{LHC Energy Increase}}{\text{Free Protons on Creation}} = 10^8$$

$$\frac{\text{Collective Potential}}{\text{Neutral Trap Depth}} = 10^3 - 10^5$$

Catching and Cooling



G. Gabrielse et al. First capture of antiprotons in a Penning trap: A kiloelectronvolt source, Phys. Rev. Lett. 57, 2504 (1986),

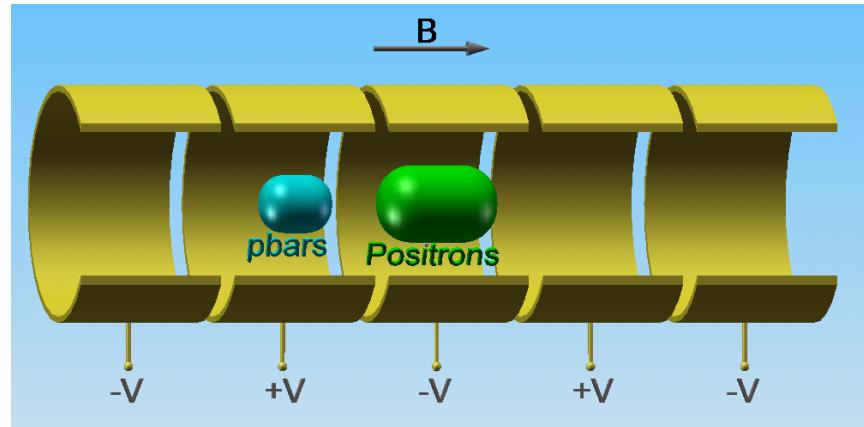
Cold Antihydrogen: Athena and Atrap (2002)

- Take \sim 10 thousand antiprotons. Cool to several Kelvin.
- Take \sim 10 million positrons. Cool to several Kelvin.
- Mix, keeping charged species cold and confined.
  **Antihydrogen**
- Techniques:
 - Atomic Physics: recombination rates.
 - Particle Physics: particle detectors.
 - Cryogenic Physics: superconducting magnet systems.
 - Plasma Physics: non-neutral plasmas.

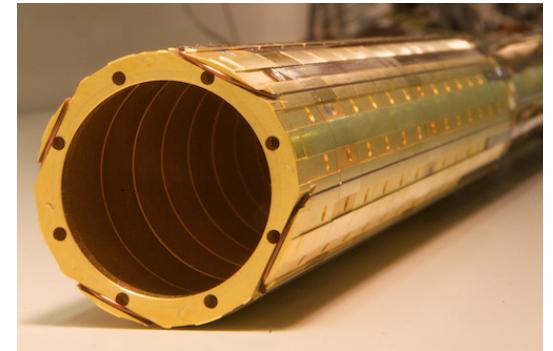
M. Amoretti, et al. (ATHENA), Production and detection of cold antihydrogen atoms, *Nature* 419, 456 (2002).

G. Gabrielse, et al., Background-free observation of cold antihydrogen with field-ionization analysis of its states, *Phys. Rev. Lett.* 89, 213401 (2002).

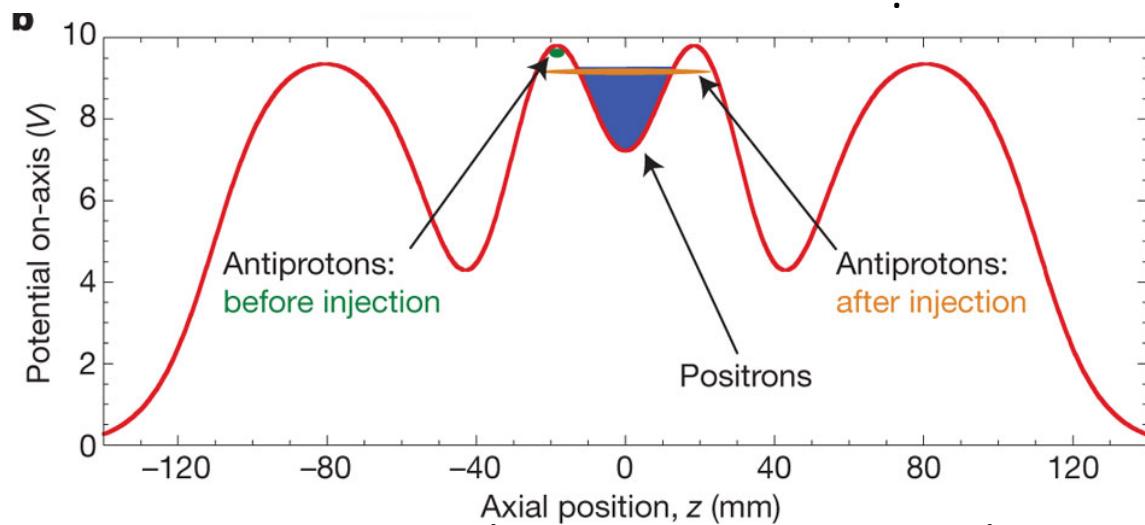
ALPHA Apparatus



Penning Malmberg Trap



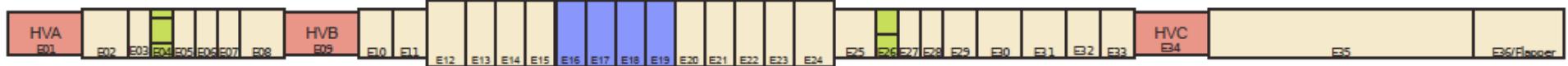
- Electrostatic well confines particles axially.
- Axial magnetic field confines particles radially



catching trap

mixing trap

positron trap



Normal Electrodes
Filtered Electrodes
Segmented Electrodes
High-Voltage Electrodes

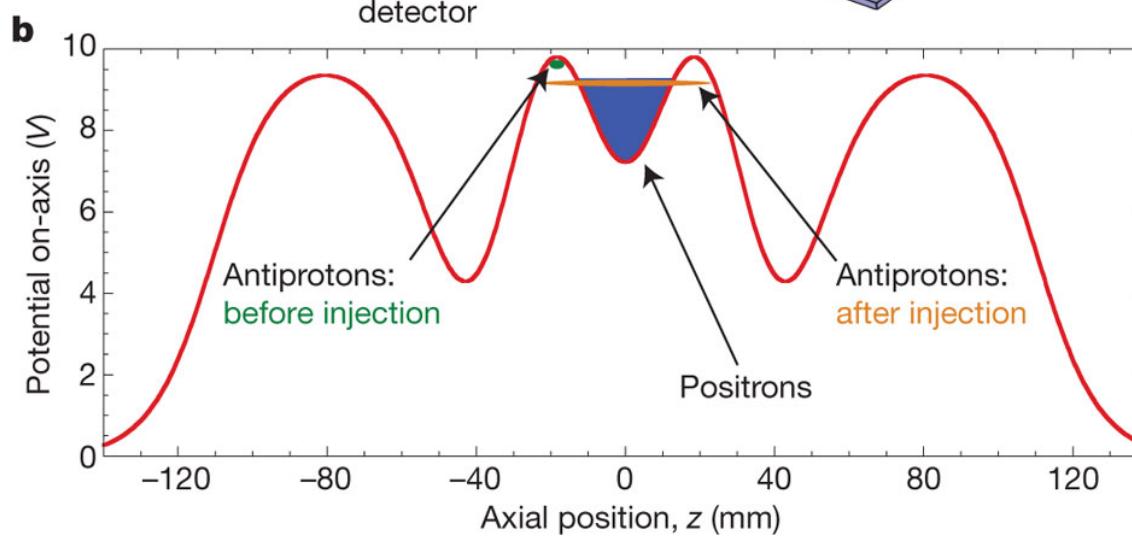
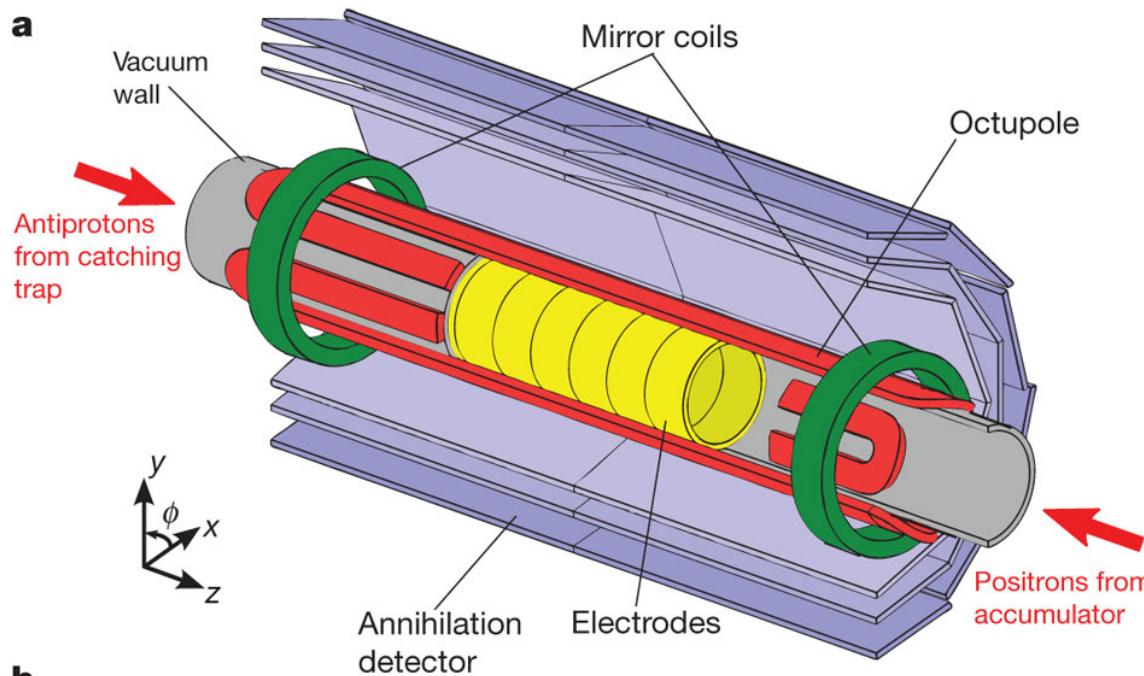


Antiproton Phase Space Manipulations prior to synthesis of antihydrogen

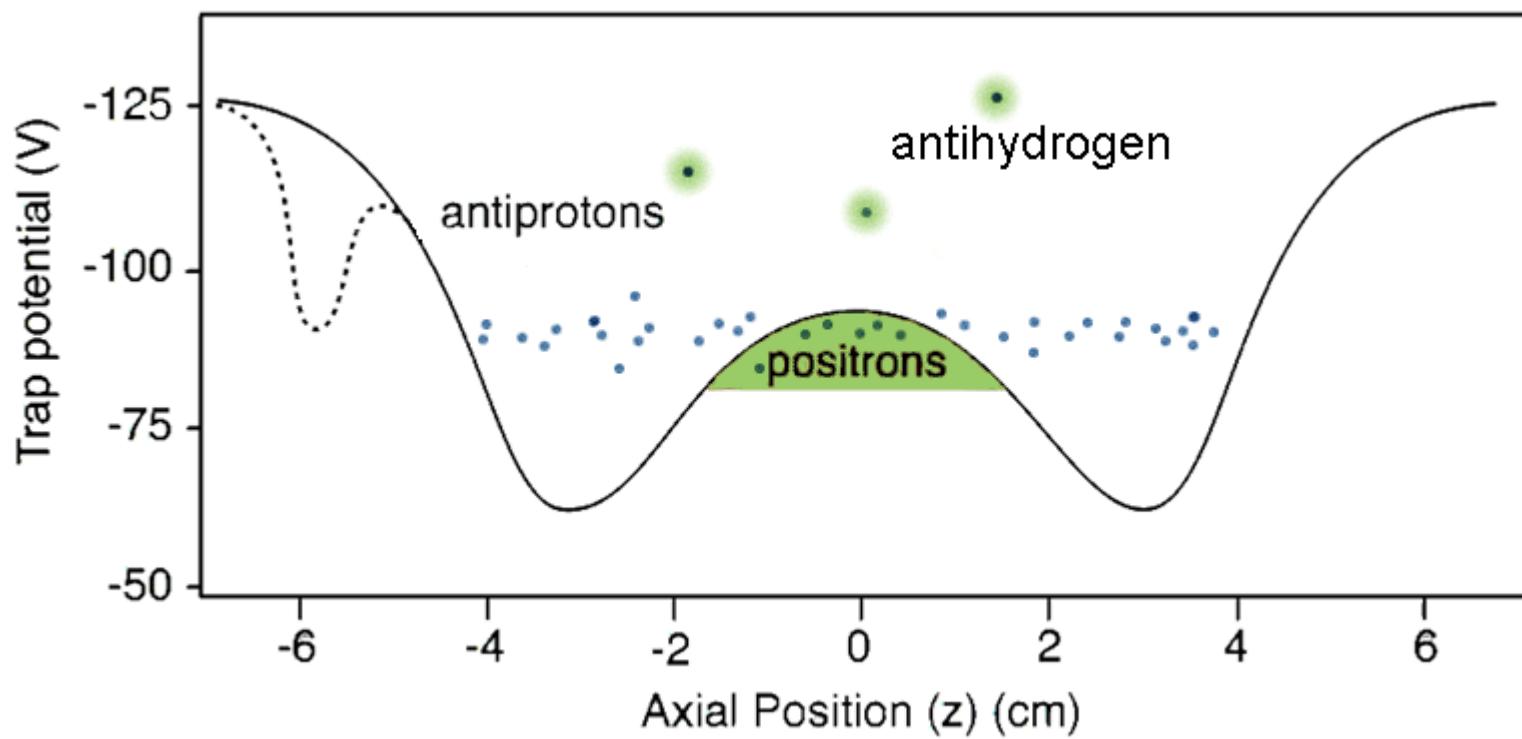
- **Compression:** (apply rotating wall torque to electrons and sympathetically compress antiprotons) [ALPHA PRL 2011]
- **E-Kick:** Remove electrons from the antiprotons (quickly lower and raise a potential well).
- **Evaporative Cooling:** Slightly lower potential well to remove hottest antiprotons by lowering potential well. [ALPHA PRL 2010]

ALPHA
 α

Creating Antihydrogen



Mixing

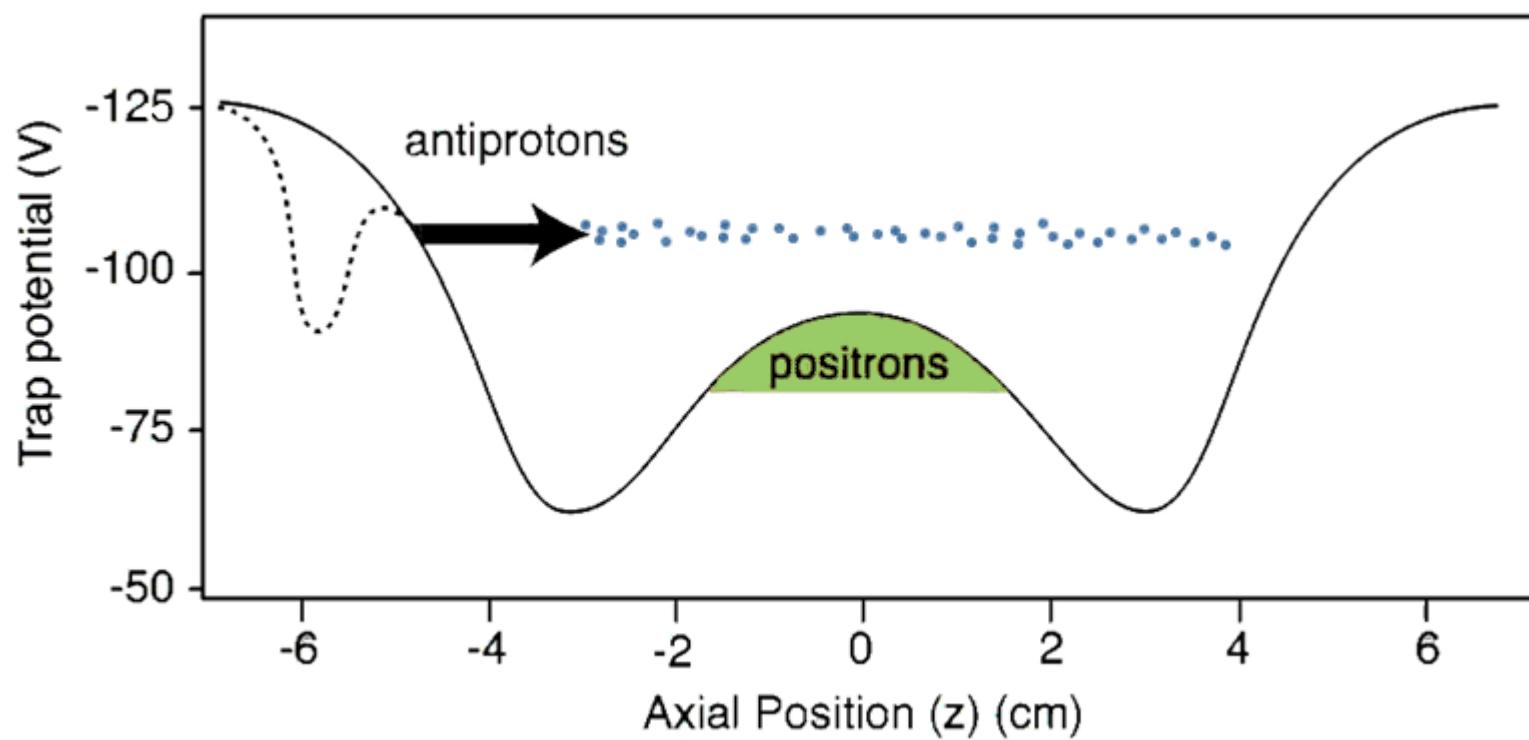


M. Amoretti, et al. (ATHENA), Production and detection of cold antihydrogen atoms, *Nature* 419, 456 (2002).

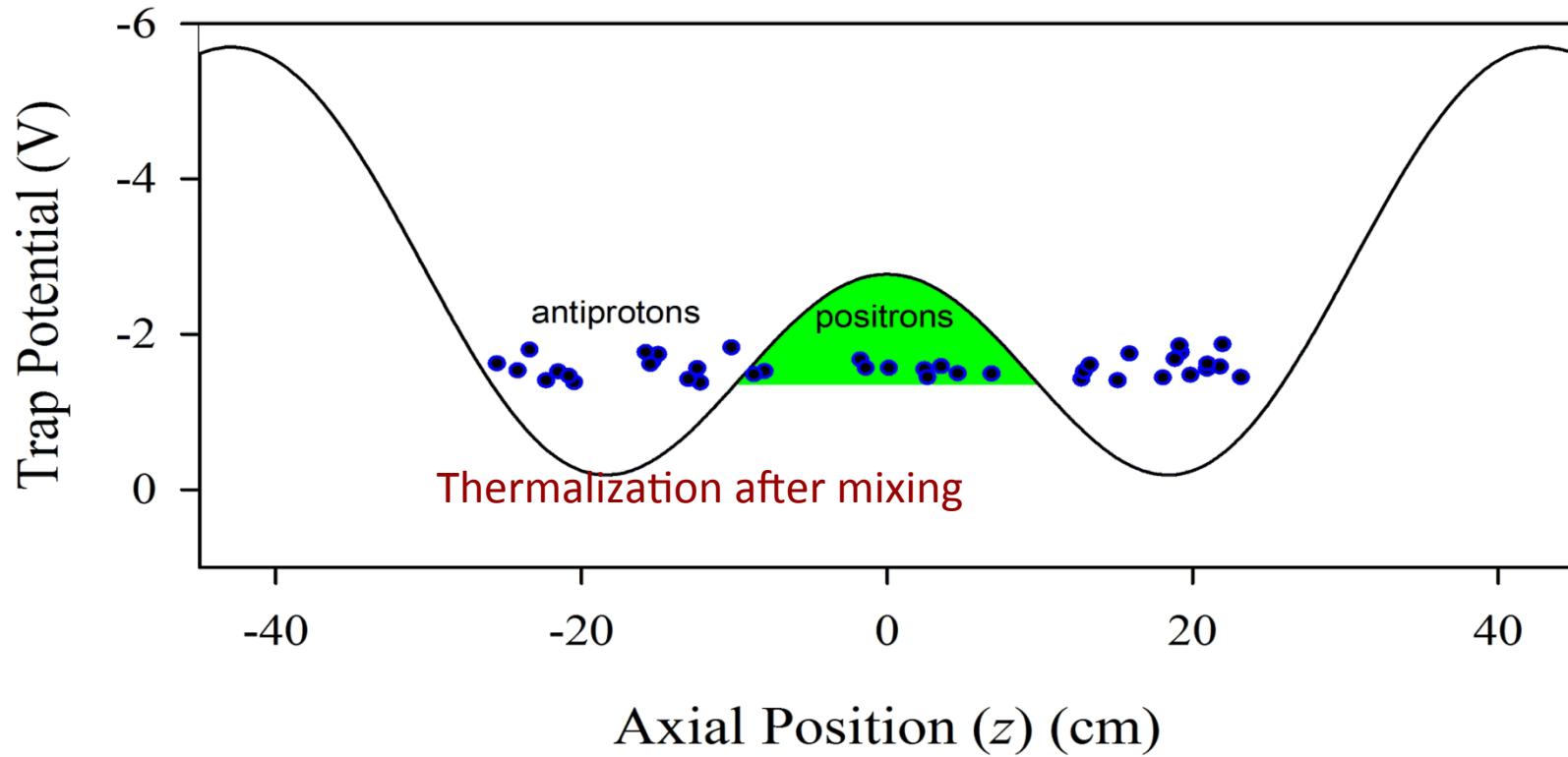
G. Gabrielse, et al., Background-free observation of cold antihydrogen with field-ionization analysis of its states, *Phys. Rev. Lett.* 89, 213401 (2002).

Energy Gain on Mixing Injection

- Standard mixing techniques impart too much energy to antiprotons.

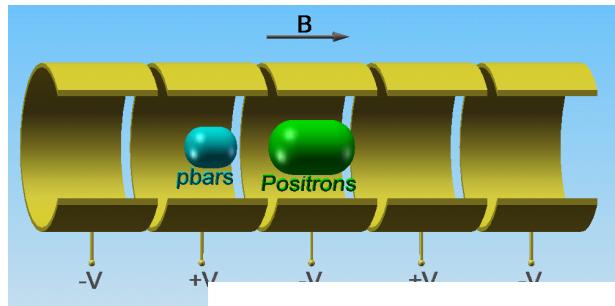


Thermalization after mixing

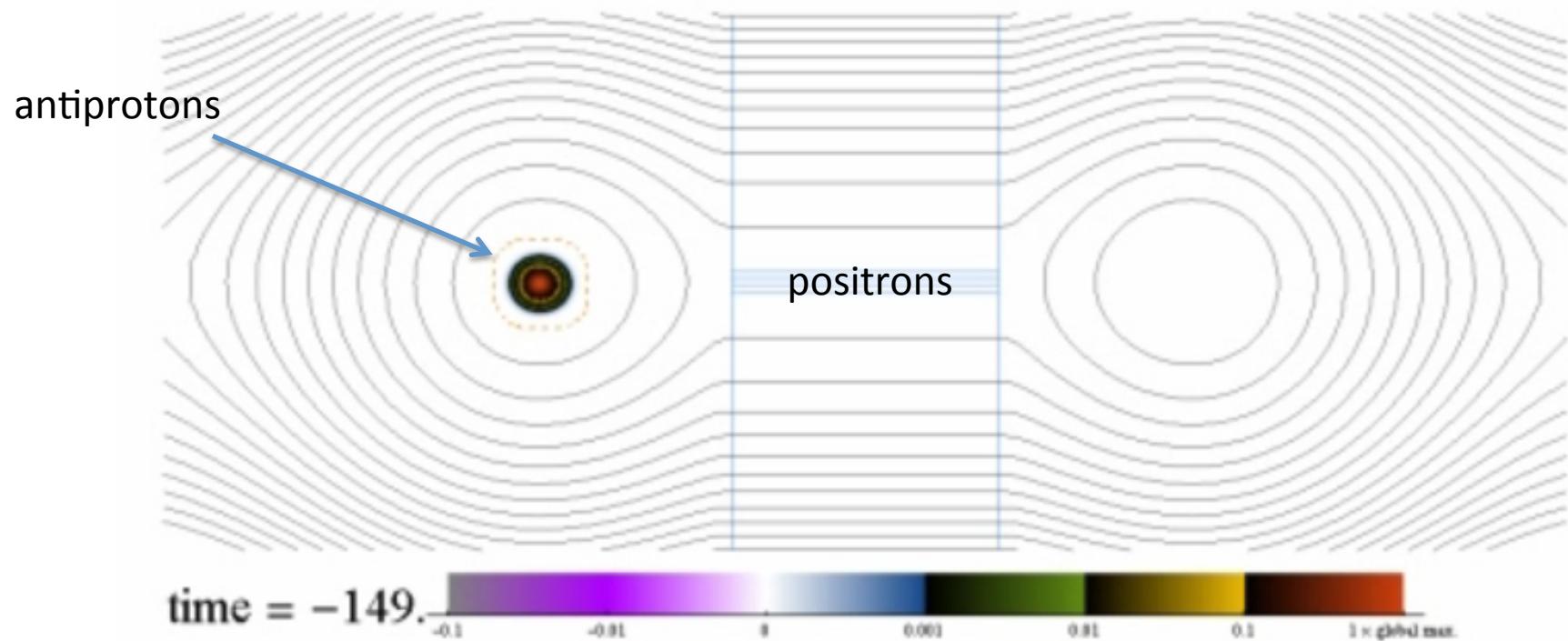


- Thermalization time scale is less than the synthesis time scale.
- Antihydrogen atoms will be created at approximately the same temperature as the positrons.
- We want a technique to excite the antiprotons that imparts minimum KE and is insensitive to fluctuations in particle number.

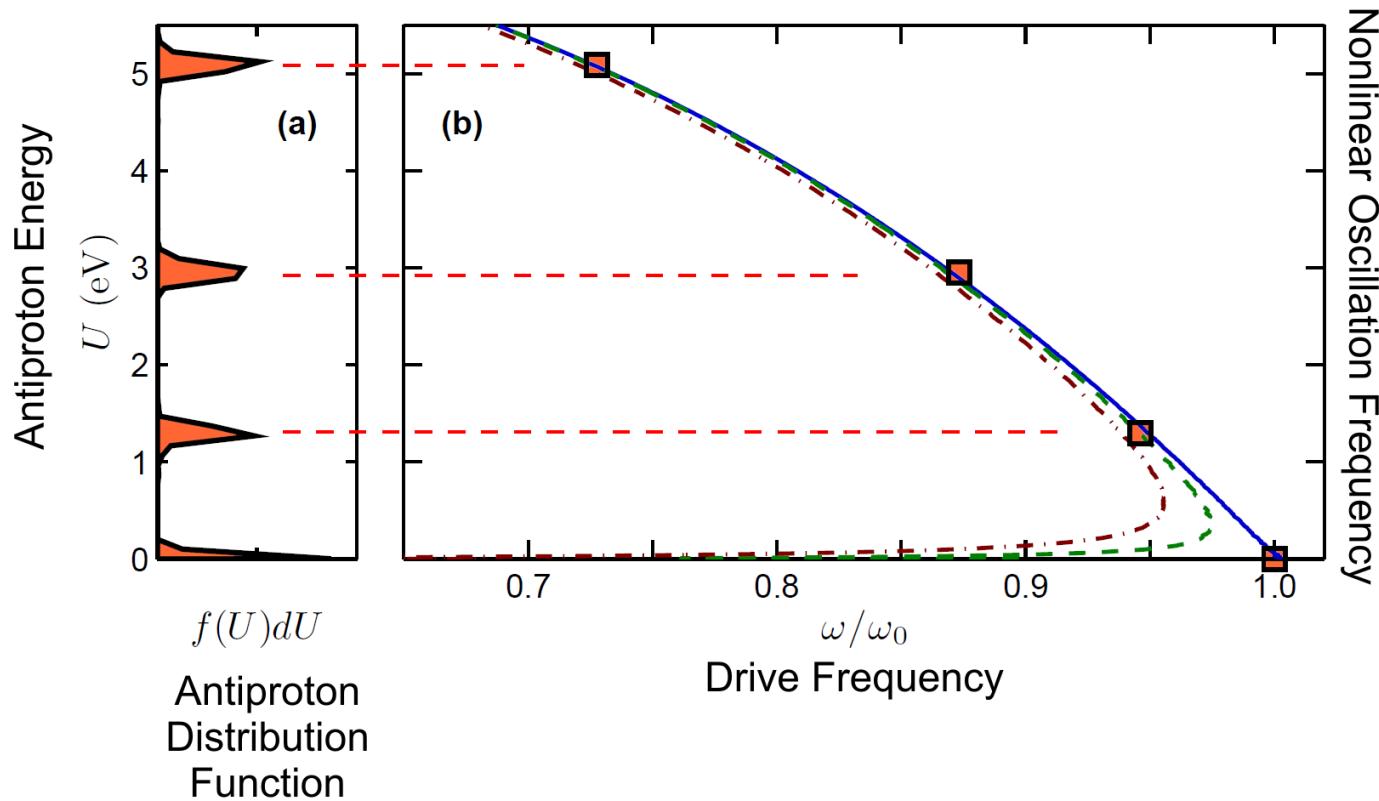
Antiproton Plasma Mixing



Vlasov Simulation for antiprotons with quasi-static positrons



Autoresonant Mixing



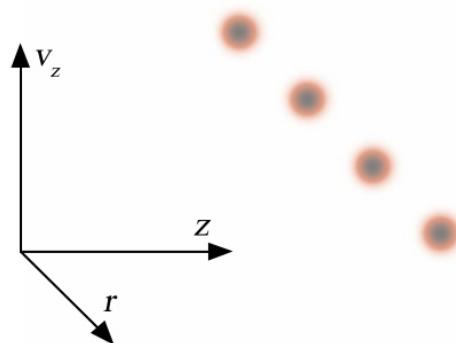
- Not obvious why the antiproton self-electric fields don't tear the antiproton cloud apart.
 - In fact, these fields are necessary to compensate for the antiproton thermal spreads.
 - Autoresonance would not work without these fields.

ALPHA, [Autoresonant excitation of antiproton plasmas](#), in press Phys. Rev. Lett., (2011).

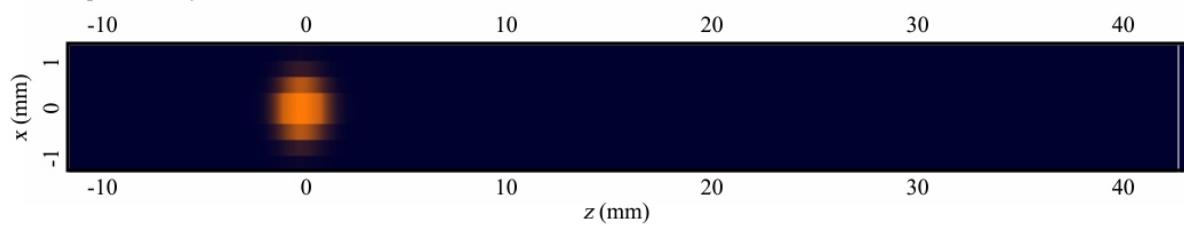
I. Barth, L. Friedland, E. Sarid, and A. G. Shagalov, [Autoresonant Transition in the Presence of Noise and Self-Fields](#), Phys. Rev. Lett., 103, 155001 (2009).

Autoresonant Mixing: Radial Effects

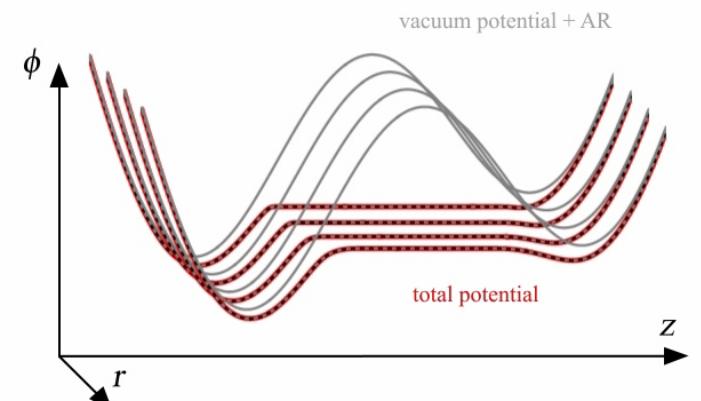
Phase space density



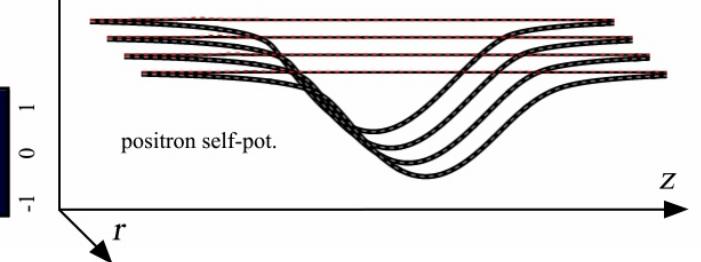
Coord. space density

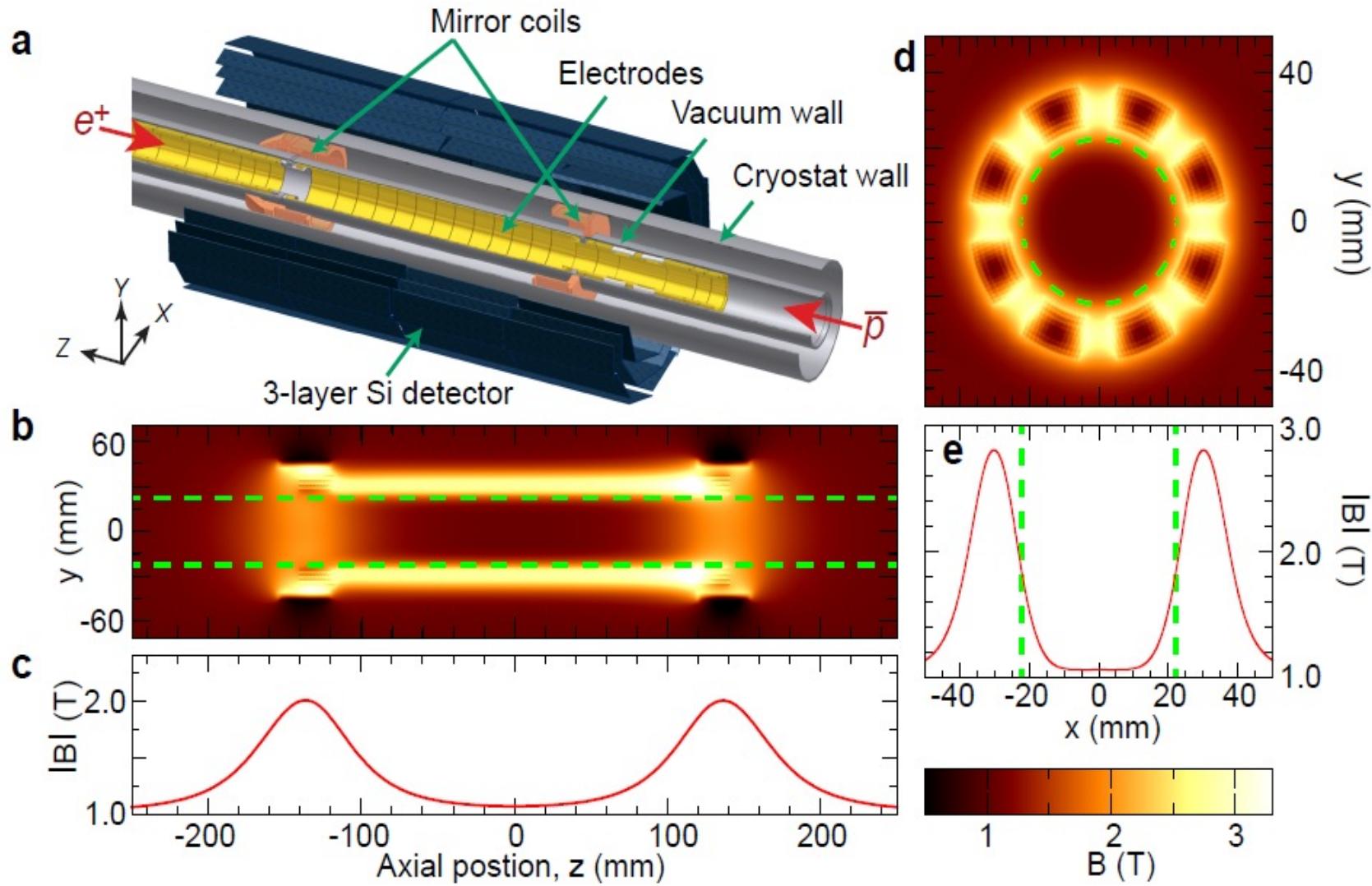


Potentials



antiproton self-pot. (10 x)

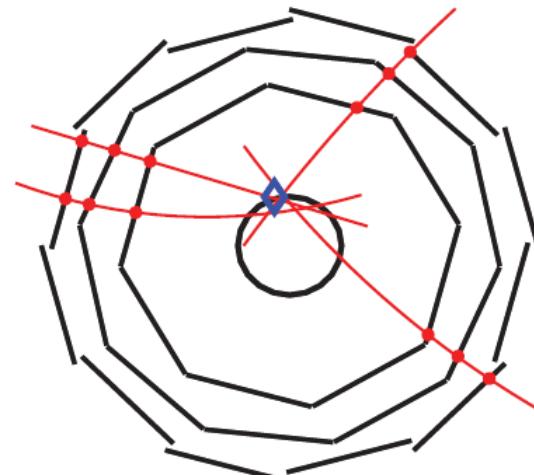




Detection of Trapped Antihydrogen

- Trapped antihydrogen search technique:
 - 1) Perform a mixing cycle to make antihydrogen.
 - 2) Destroy the electrostatic wells to sweep out any remaining antiprotons.
 - 3) Quickly ($\sim 10\text{ms}$) turn off our octupole and mirror fields. Any trapped antihydrogen then hits the walls and annihilates.
 - 4) Detect the annihilations.

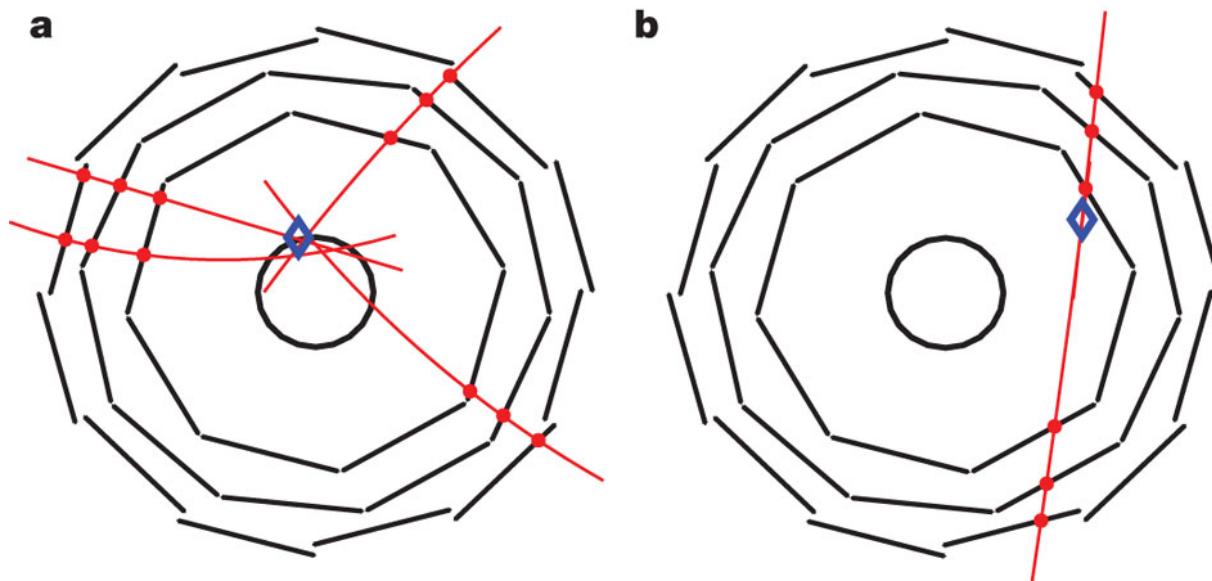
Octupole Current Decay



ALPHA [A magnetic trap for antihydrogen production](#), NIM A **566**, 746 (2006).

ALPHA, [Trapped Antihydrogen](#), Nature **468**, 673 (2010).

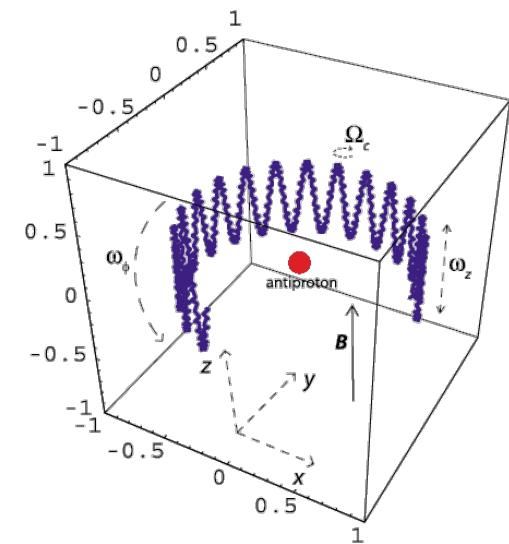
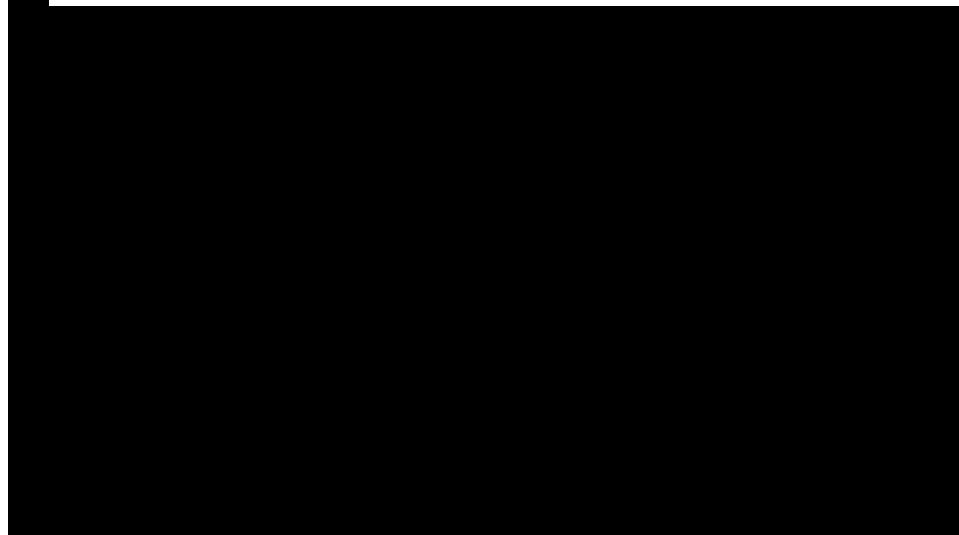
Detected antiproton annihilation and cosmic ray events.



Initially we have ExB Atoms

- Antihydrogen atoms are highly excited ExB guiding center atoms.

- We need antihydrogen in the ground state long enough to conduct precision experiments

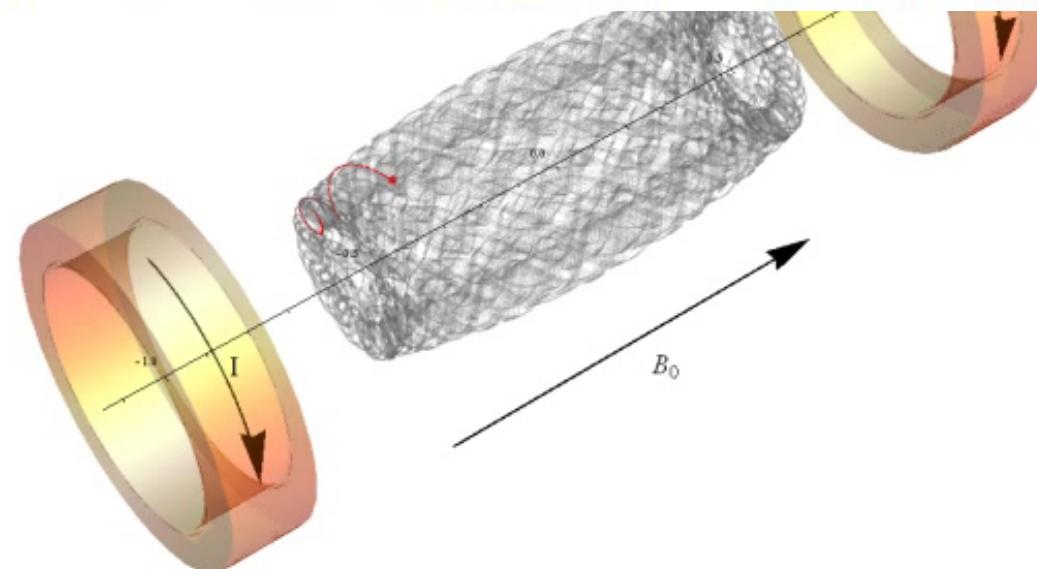
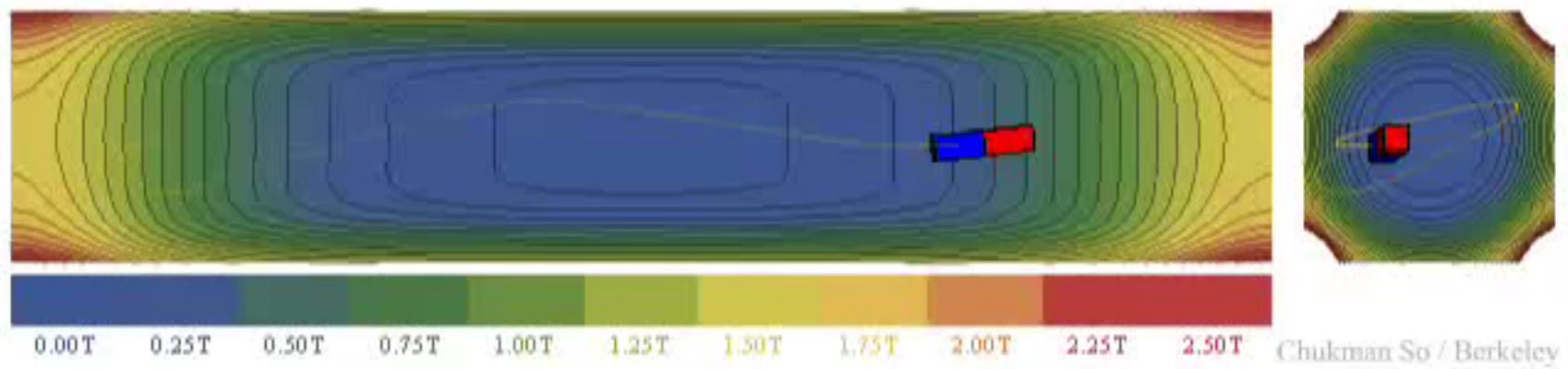


E.M. Bass and D.H.E. Dubin, [Antihydrogen formation from antiprotons in a pure positron plasma](#), Phys. Plasma **16**, 012101 2009.

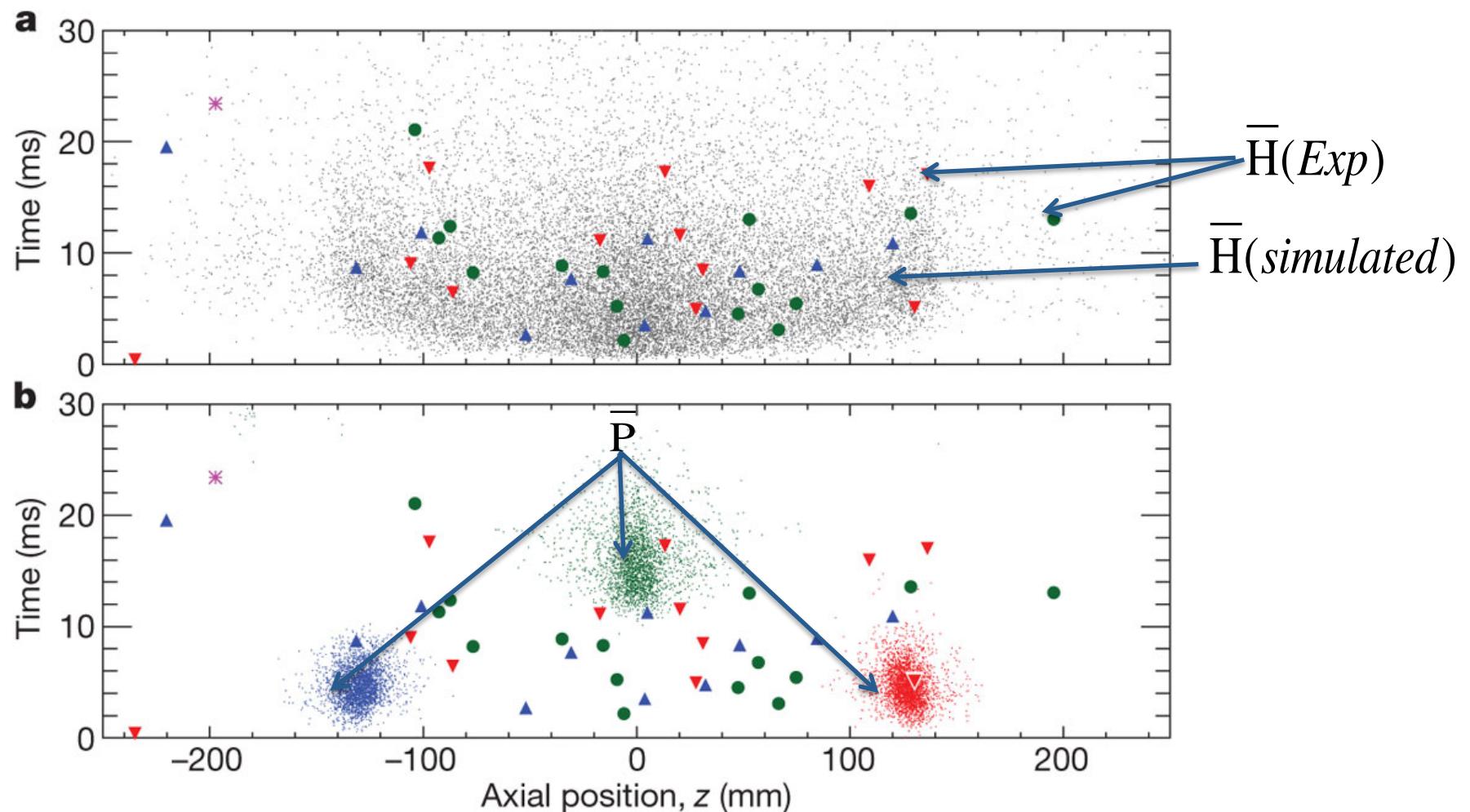
M.E. Glinsky and T.M. O'Neil [Guiding Center Atoms: Three-body Recombination in a Strongly Magnetized Plasma](#), Phys. Fluids B, **3**, 1279 1991.

Mirror Trapped Antiprotons?

- We can distinguish trapped antihydrogen from mirror trapped antiprotons.



Distributions of released antihydrogen atoms and antiprotons.



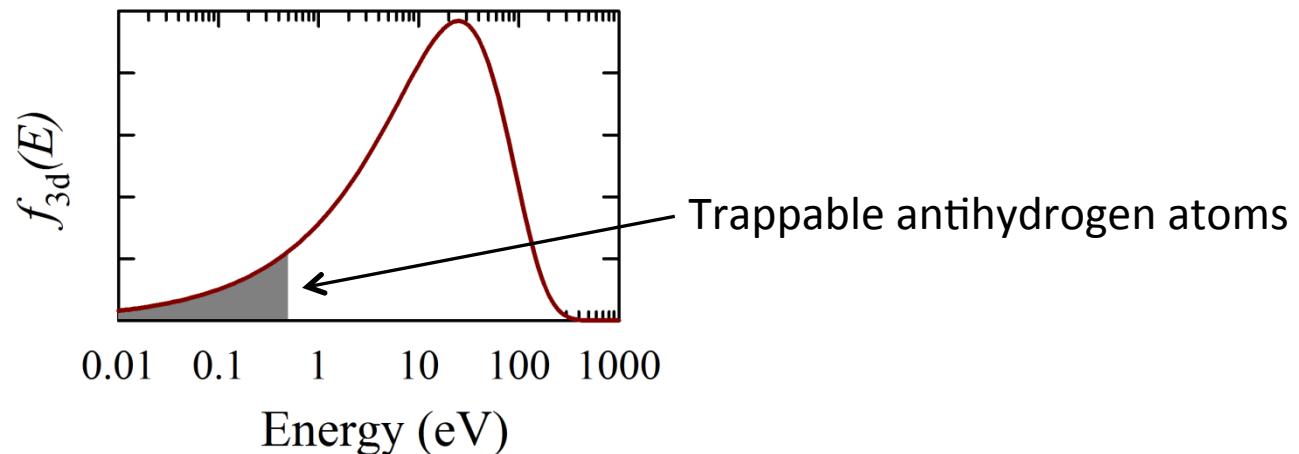
GB Andresen *et al. Nature* (2010)

38 real anti-atom annihilations (circles and triangles) match simulated anti-atom distribution and not simulated antiproton distribution.

nature

Trapped Antihydrogen Synthesis Rate

- We make antihydrogen with a temperature of ~50K.
- Our trap depth is ~0.5K!
- We trap only the coldest antiprotons in the thermal distribution.

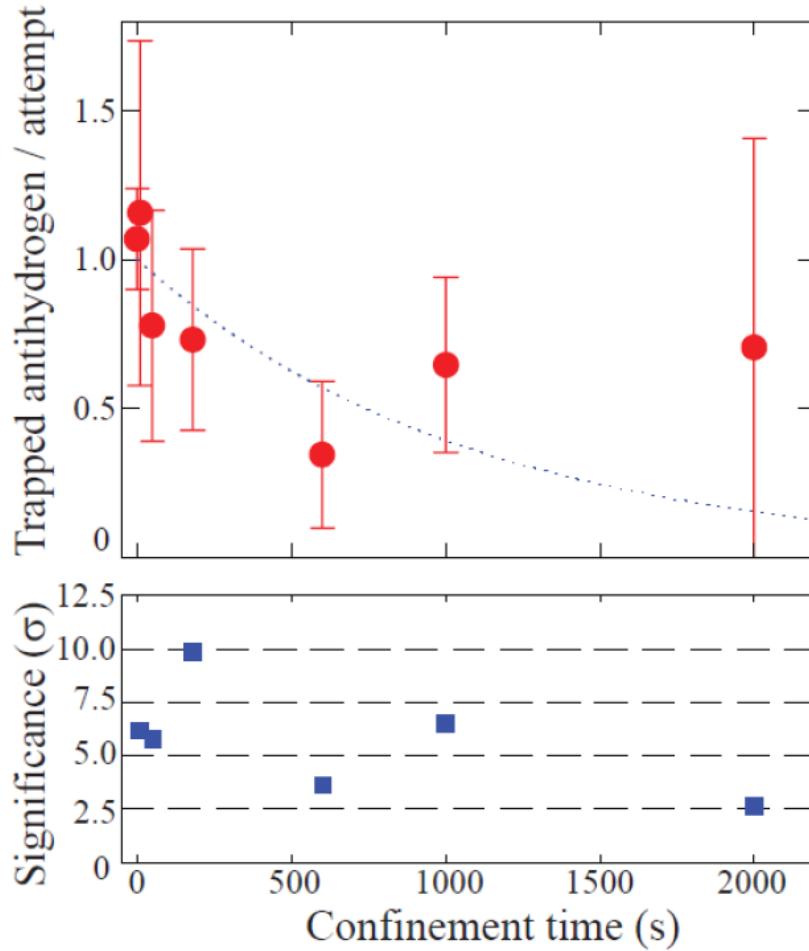


Approximately one atom in ten thousand is potentially cold enough.

- Average mixing attempt has ~ten thousand antiprotons...
- We trap one antihydrogen atom in every attempt.
- Attempts take ~15minutes.

Antiprotons into ALPHA	Captured & cooled	Antihydrogen produced	Antihydrogen captured
Few 10^7	2×10^4	10^4	~ 1

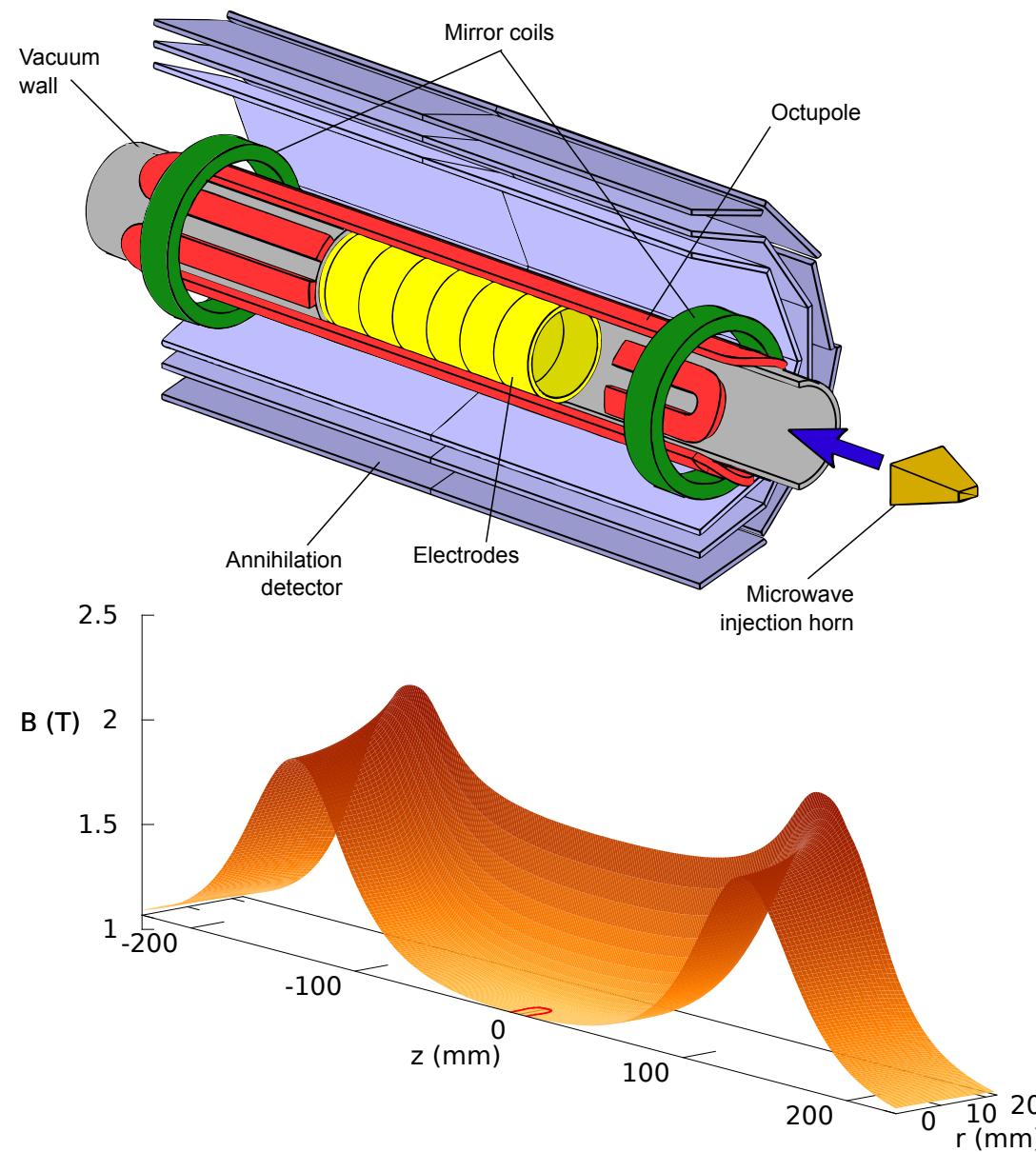
Trapped Antihydrogen Lifetime

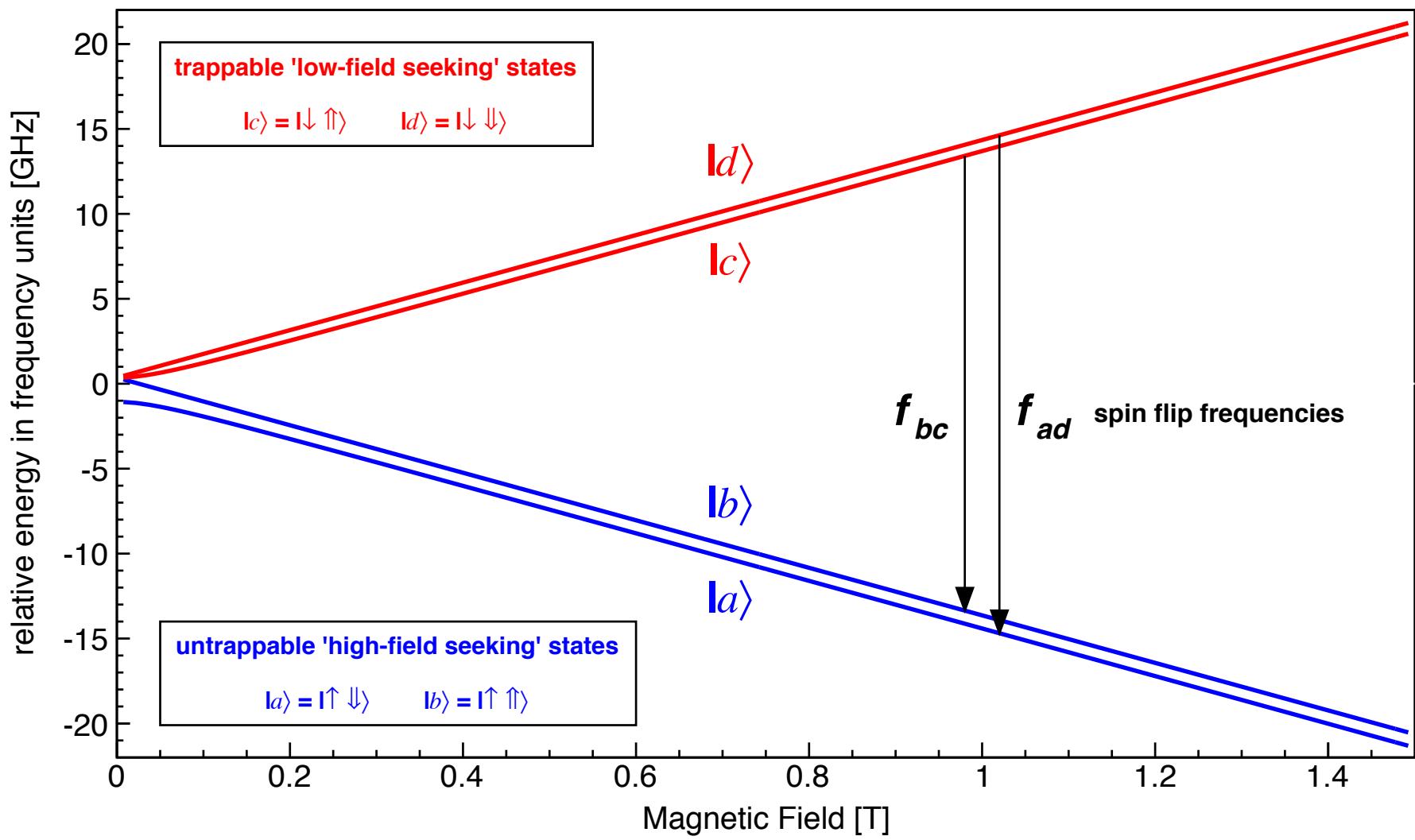


Hold Time (ms)	Left Bias Trials	No Bias Trials	Right Bias Trials	Total Trials	Total Trials
0.172	50	29	11	90	860
0.42	106		16	122	292
10.42	4			4	6
50.42	4			4	13
180.42	8		3	11	34
600.42			2	2	12
1000.42	4		1	5	16
2000.42			1	1	3
3600.42					1
Total	176	29	34	239	
Trials	641	357	239		1237

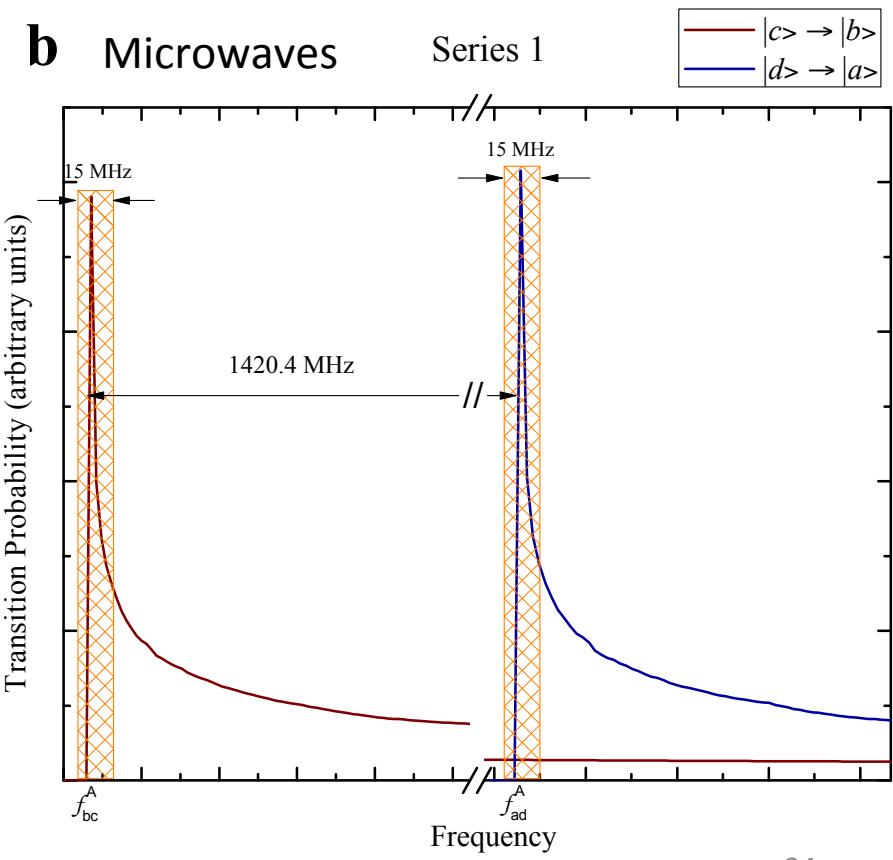
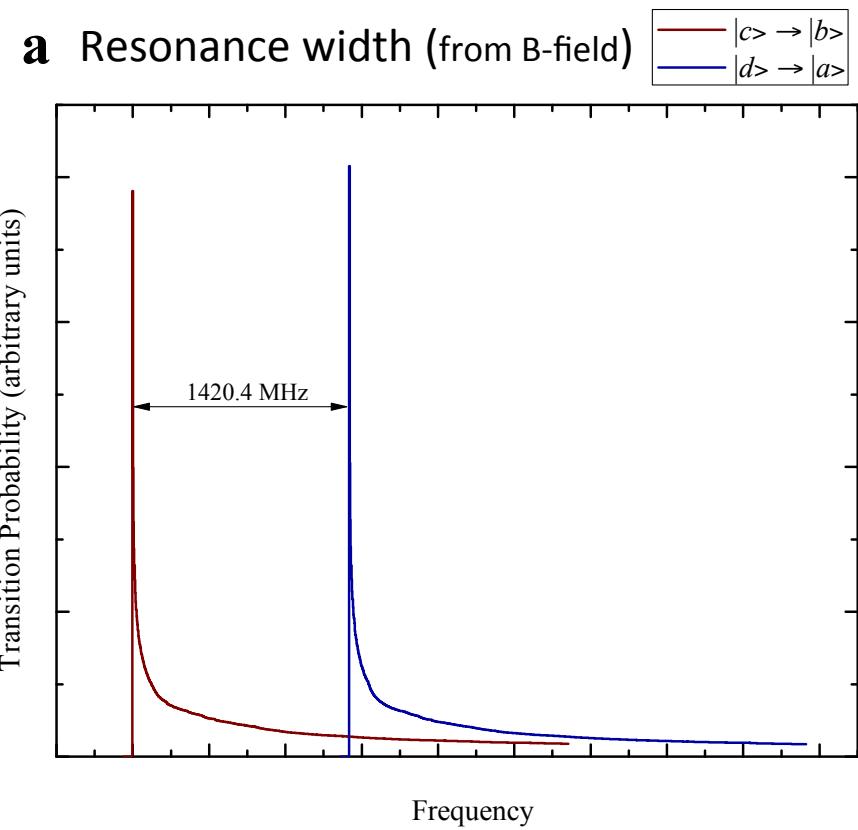
Calculations suggest that all atoms trapped for more than a few seconds will have decayed to the ground state.

Resonant Interaction with Antihydrogen

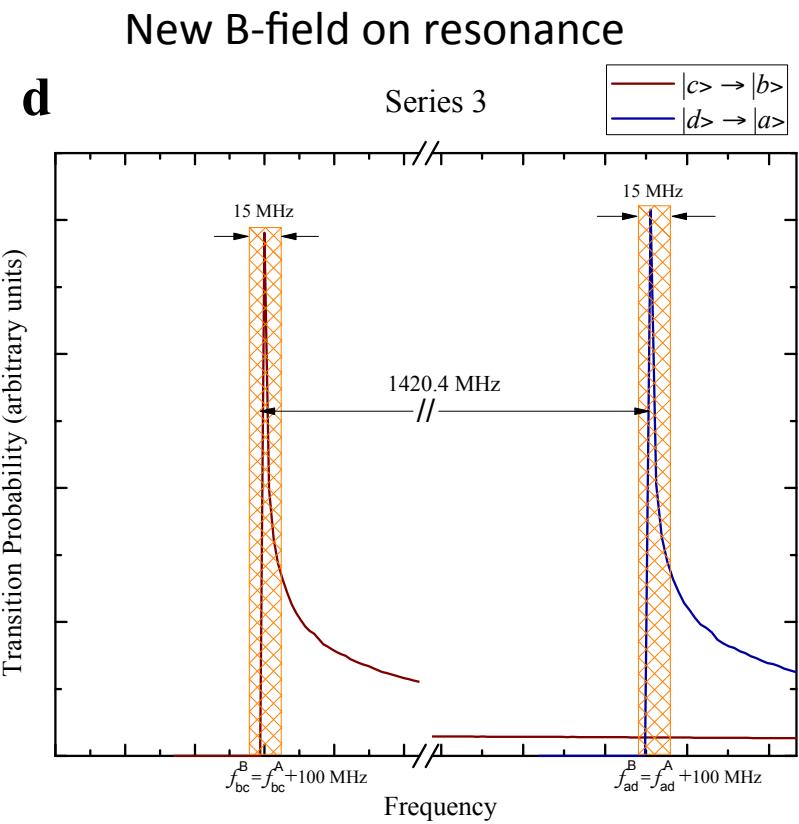
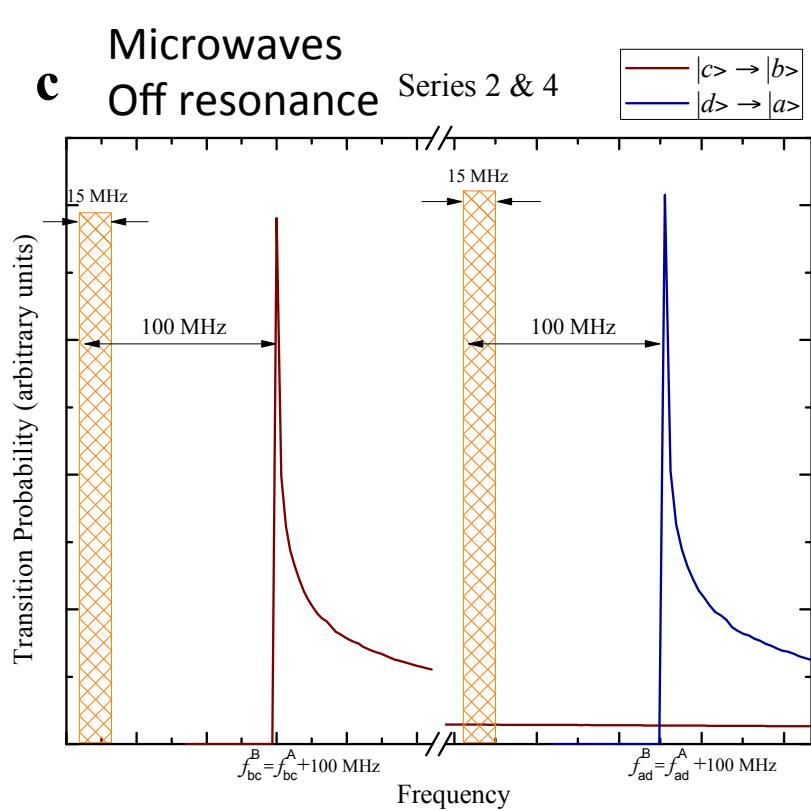




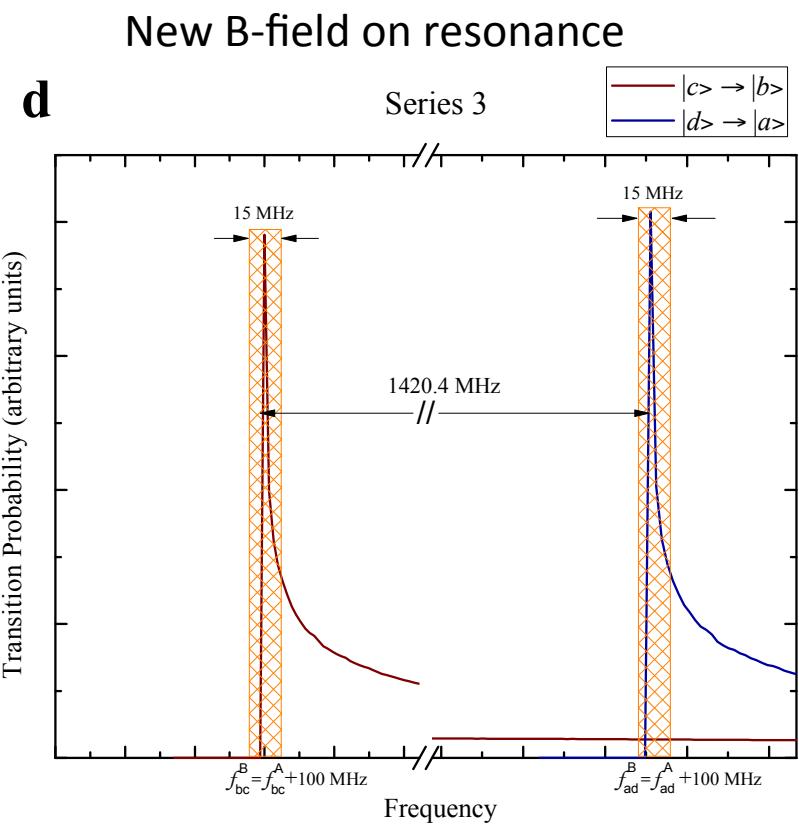
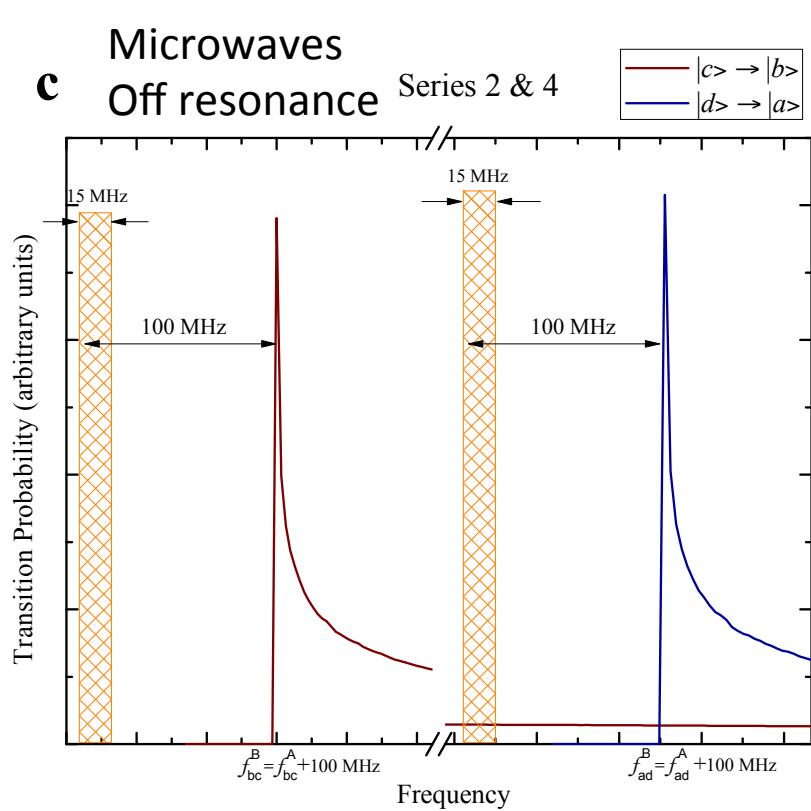
Microwave Experiments



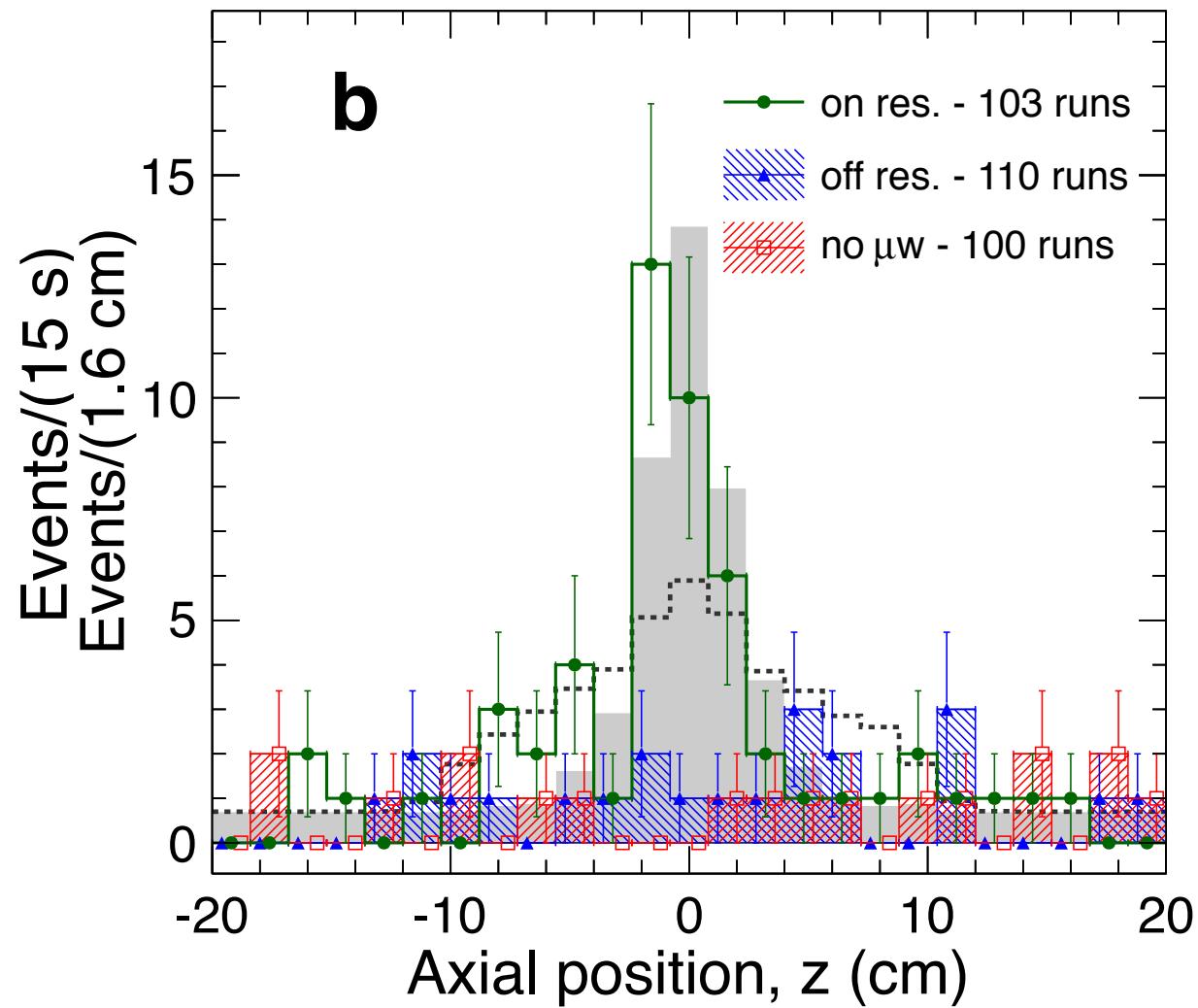
Microwave Experiments



Microwave Experiments



Microwave Probing of Antihydrogen





Antihydrogen Trapping and Manipulation

LETTER

doi:10.1038/nature09610

Trapped antihydrogen

G. B. Andresen¹, M. D. Ashkezari², M. Baquero-Ruiz³, W. Bertsche⁴, P. D. Bowe¹, E. Butler⁴, C. L. Cesar⁵, S. Chapman³, M. Charlton⁴, A. Deller⁴, S. Eriksson⁴, J. Fajans^{3,6}, T. Friesen⁷, M. C. Fujiwara^{8,7}, D. R. Gill⁸, A. Gutierrez⁹, J. S. Hangst¹, W. N. Hardy⁹, M. E. Hayden², A. J. Humphries⁴, R. Hydomako⁷, M. J. Jenkins⁴, S. Jonsell¹⁰, L. V. Jorgensen⁴, L. Kurchaninov⁸, N. Madsen⁴, S. Menary¹¹, P. Nolan¹², K. Olchanski⁸, A. Olin⁸, A. Povilus³, P. Pusa¹², F. Robicheaux¹³, E. Sarid¹⁴, S. Seif el Nasr⁹, D. M. Silveira¹⁵, C. So³, J. W. Storey⁴, R. I. Thompson⁷, D. P. van der Werf⁴, J. S. Wurtele^{3,6} & Y. Yamazaki^{15,16}



ARTICLES

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Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration*

Atoms made of a particle and an antiparticle are unstable, usually surviving less than a microsecond. Antihydrogen, made entirely of antimatter, is believed to be stable, and it is this longevity that holds the promise of precision studies of antimatter atoms. We have recently demonstrated trapping of antihydrogen atoms by slowing them after

LETTER

Resonant quantum transitions in trapped antihydrogen atoms

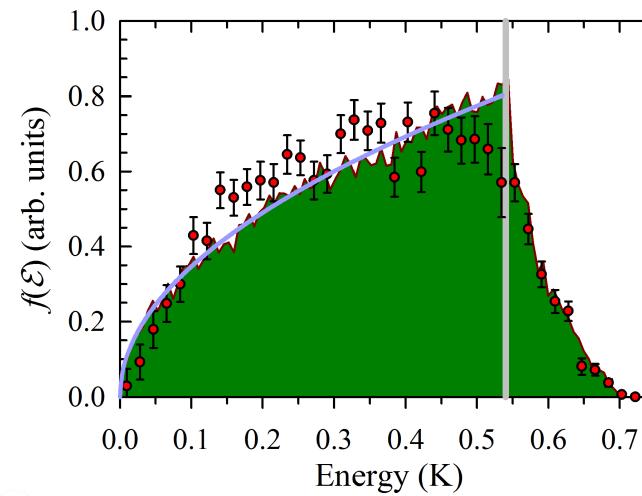
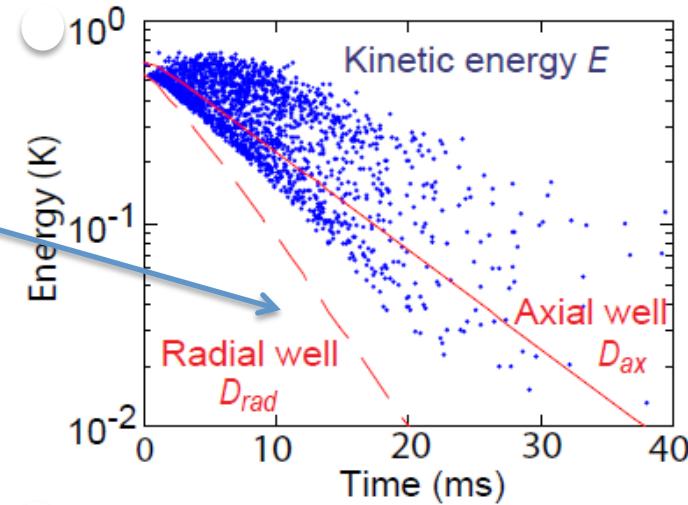
Nature, online November 2010
Physics Breakthrough of the Year (with ASACUSA),
2010 Physics World (UK)
One of the top ten physics stories of 2010 - AIP
Most clicked-on story on Nature website for a 2010

- Nature Physics, online June 2011
- First **ground state** antihydrogen
- Important implications for future spectroscopy gravitational studies, laser cooling?
- More press circus...

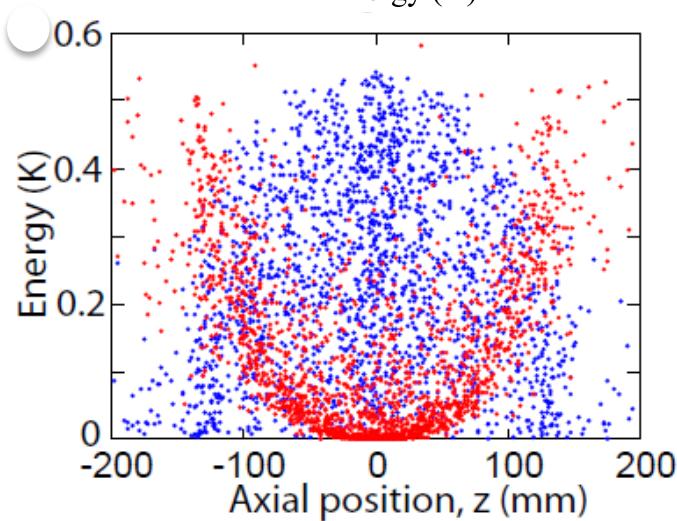
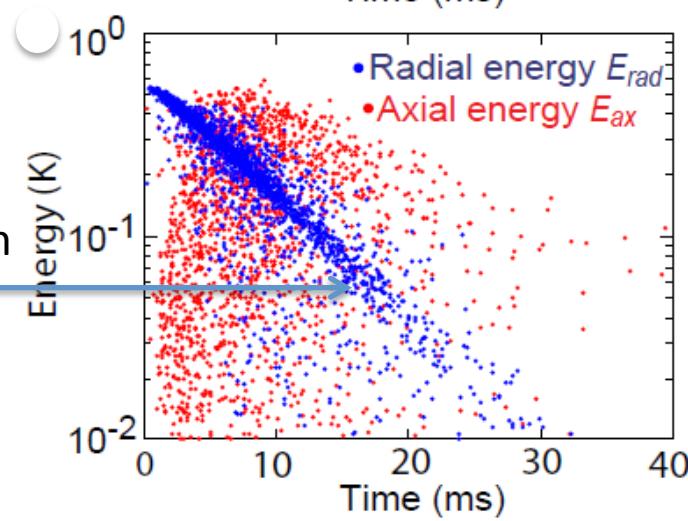
- Nature, online 7 March, 2012
- First measurement on an antimatter atom
- Shows that it is possible to do physics with few atoms
- ...but we really want x10 (or higher) trapping rate and laser cooling

Antihydrogen Trap Dynamics

Radial well falls off quickly



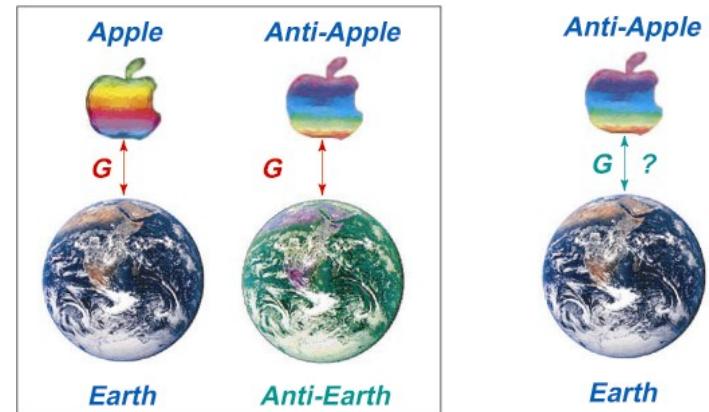
Radial Energy Correlated with time



Can ALPHA See the Effects of Gravity?

- There are many powerful indirect measurements of the effect of gravity on antimatter.
 - All these searches relied on theoretical models like
 - CPT and its postulated extensions.
 - Matter-antimatter virtual pairs.
- There have been no “free fall,” model independent measurements.
- ALPHA’s primary goal is spectroscopy.
 - We have made no deliberate tests of gravity.
 - Is there an influence of gravity on ALPHA’s data?

Weak Equivalence



Can ALPHA See the Effects of Gravity?

- Equation of motion for antihydrogen atoms in a magnetic trap and gravity:

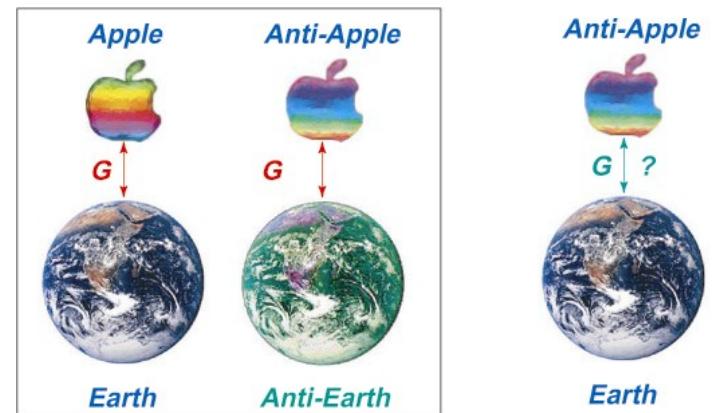
$$M \frac{d^2 \vec{x}}{dt^2} = \underbrace{\nabla(\vec{\mu}_{\bar{H}} \cdot \vec{B})}_{\text{Trapped: } -\mu_{e+} \nabla B} - M_g g \hat{y}$$

- Define the F to be the ratio of the gravitational mass to the inertial mass.

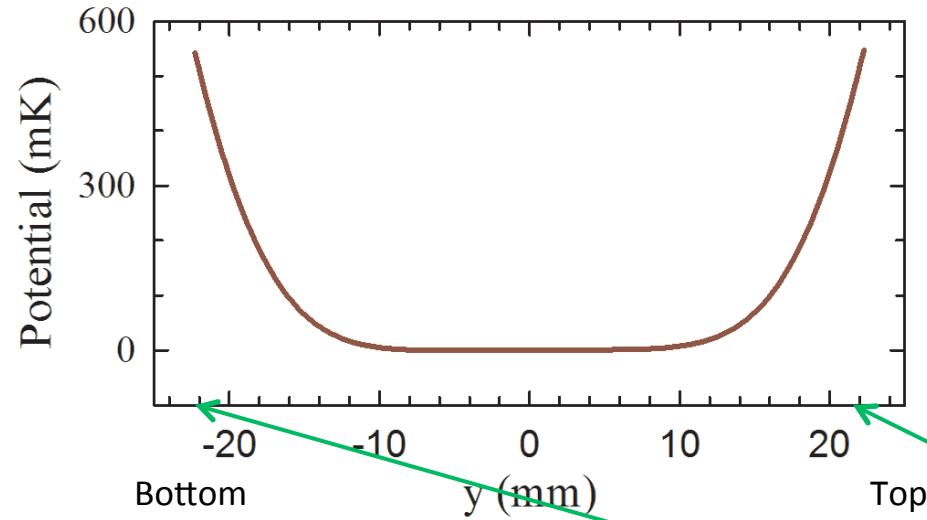
$$F = \frac{M_G}{M}$$

Weak Equivalence

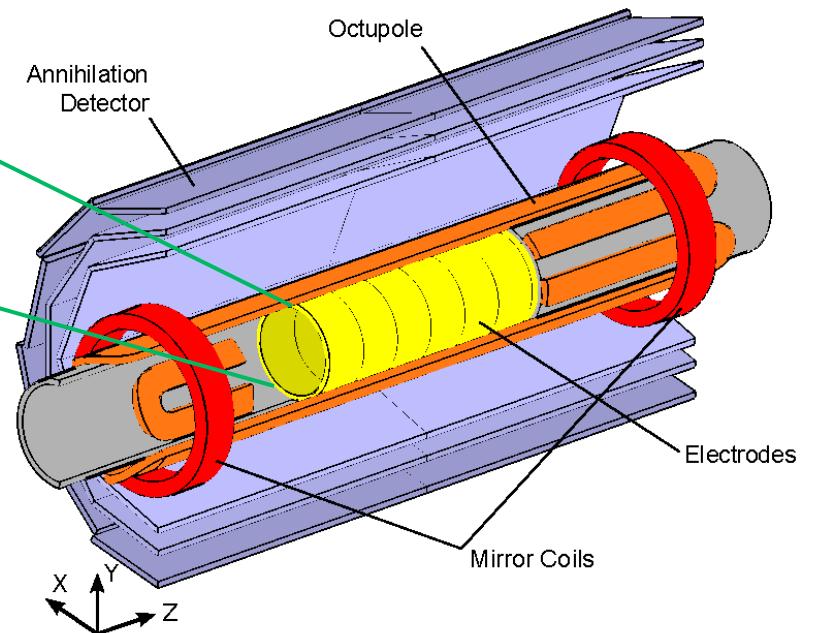
- $F=1$ is standard gravity.
- $F=-1$ is “standard” antigravity.
- $F=100$ is anomalously strong gravity



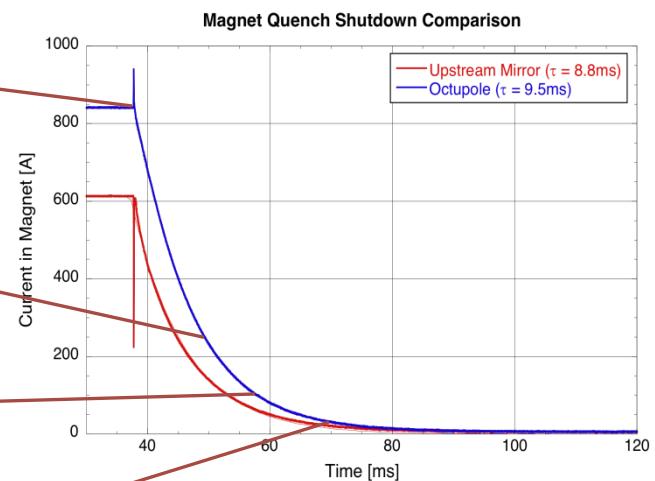
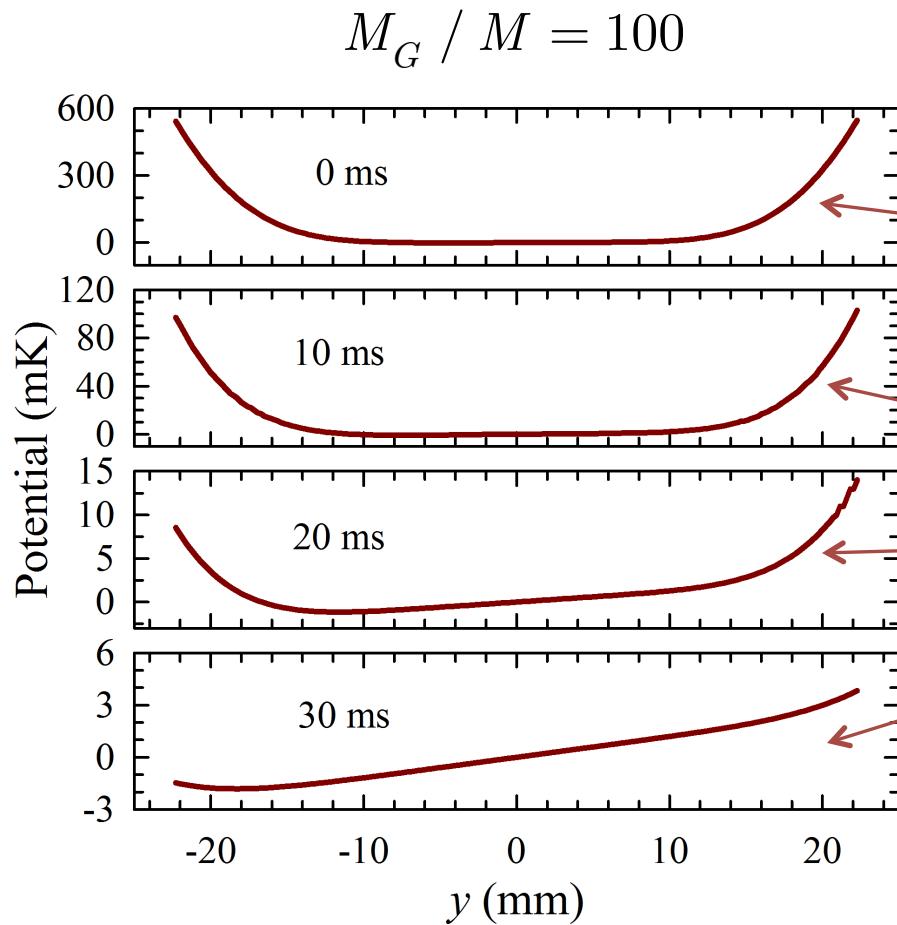
Effect of Gravity of Minimum-B Potential Well



Trap diameter is 44.55mm.

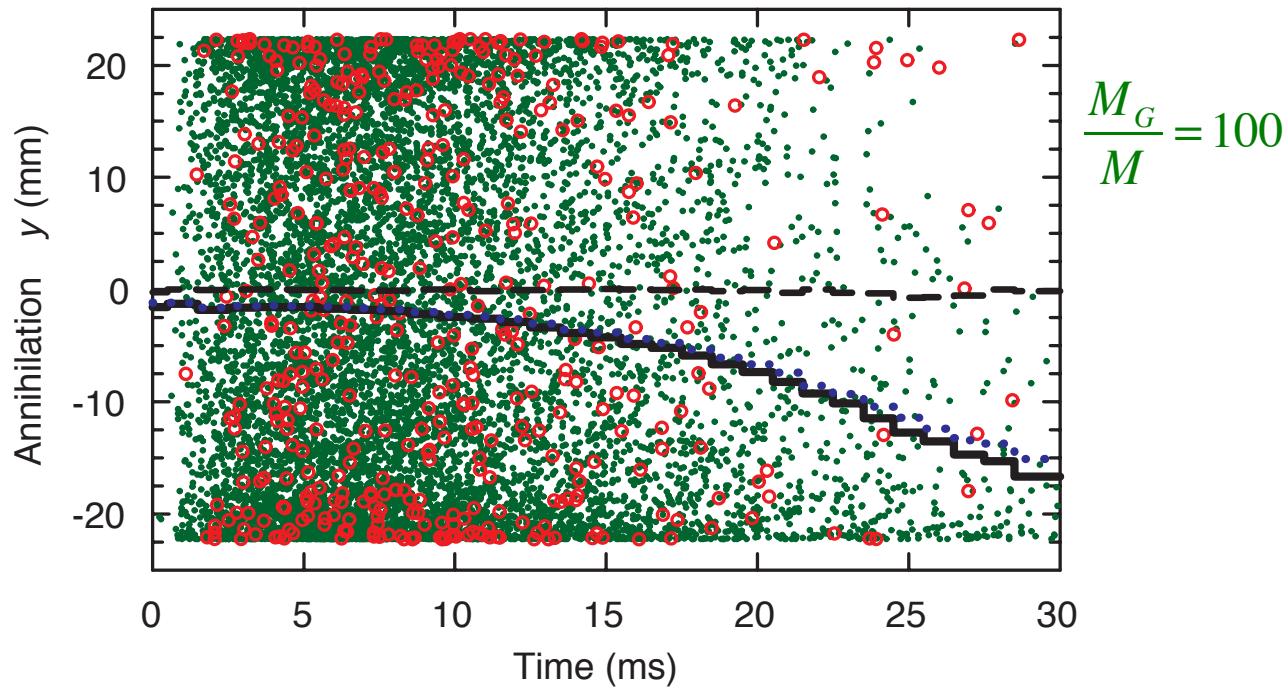


Effect of Gravity of Minimum-B Potential Well



- Sensitivity improved by “automatic” adiabatic cooling of the antihydrogen atoms.

Vertical annihilation as a function of time: “Strong Gravity” vs actual data



Green Points: Antihydrogen simulations (10^4) with $M_G / M = 100$

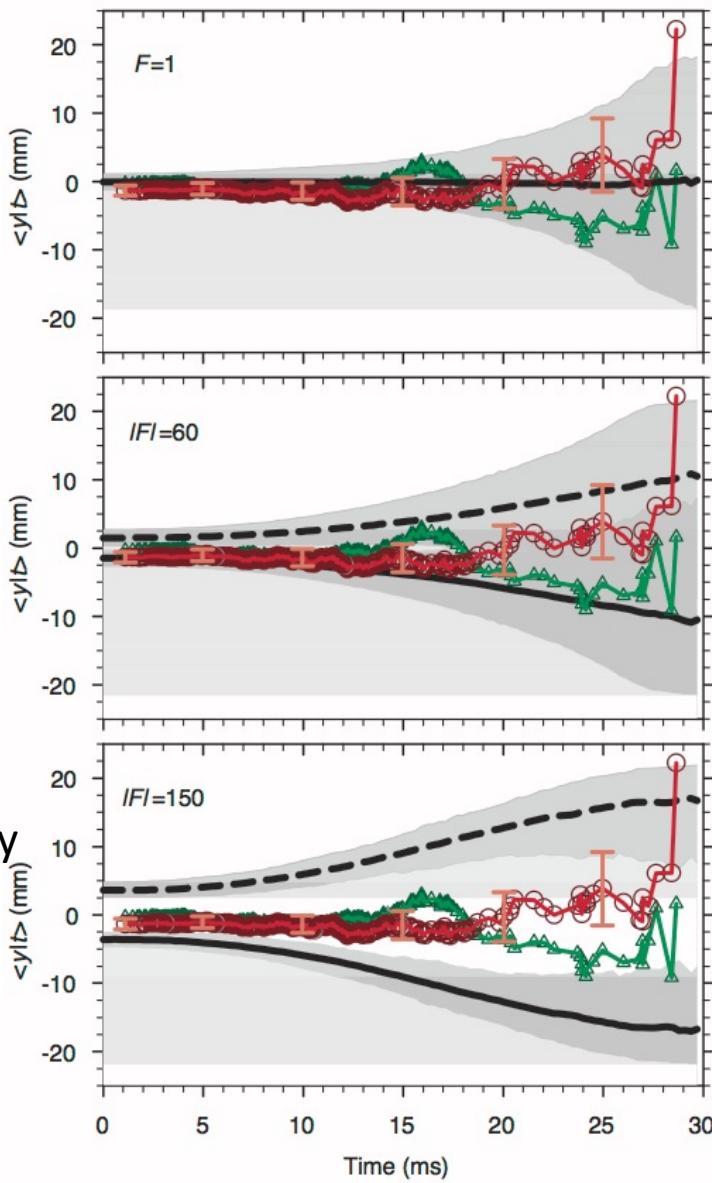
Solid Black Line: 1ms binned average of green points.

Dashed black line: binned average for $M_G / M = 1$

Red Circles: 434 antihydrogen atom annihilations on the detector.

Reverse Cummulative Analysis

Usual gravity



$$\text{Red } \circ \quad \langle y|\tau \rangle = \frac{1}{N(\tau)} \sum_n y_n \text{ (Data)}$$

$N(\tau) = \#$ annihilations after time τ

y_n = vertical position of annihilations with $t > \tau$.

Solid Black lines: simulation results for normal gravity down.

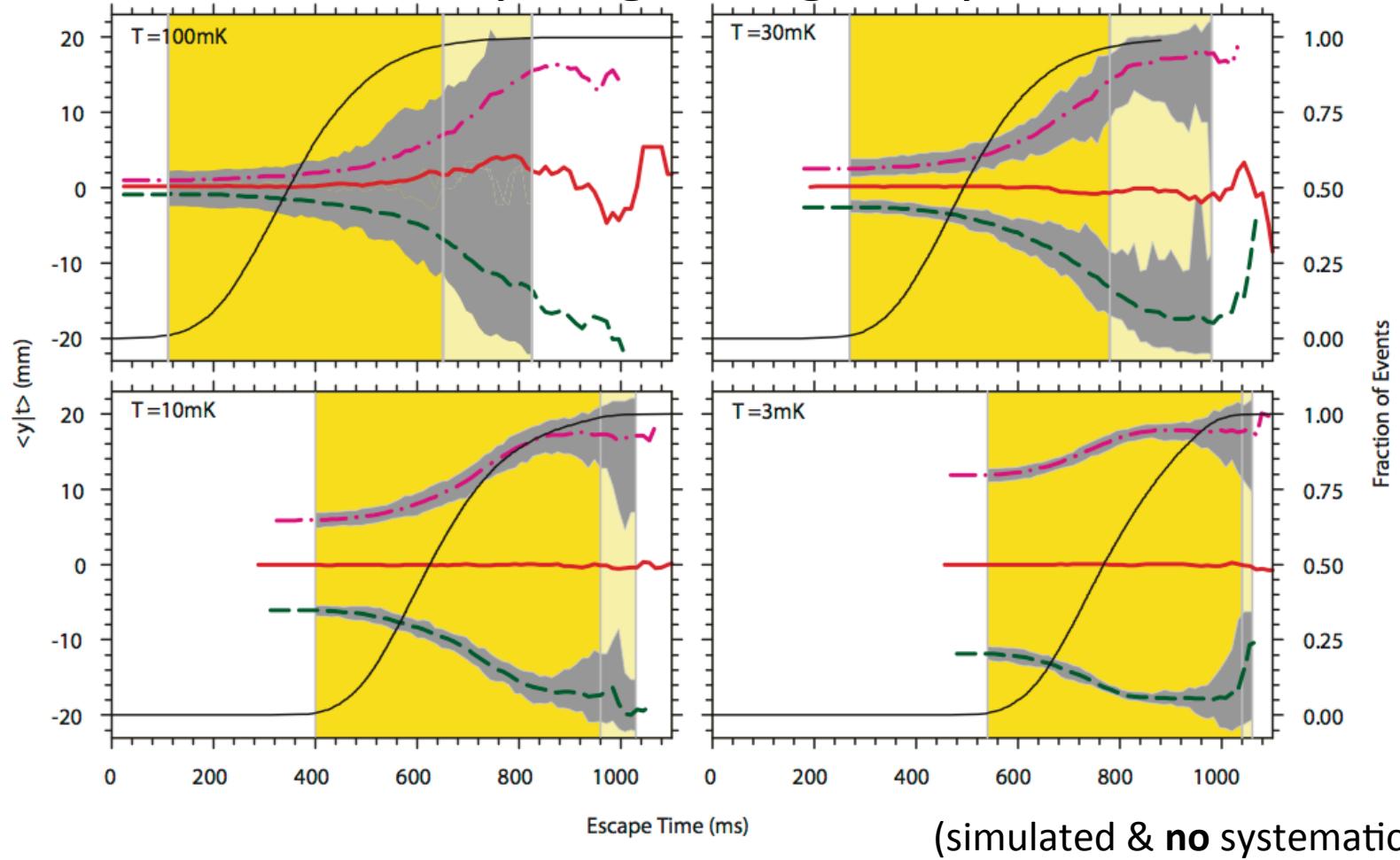
Dashed Black lines: simulation results for 'antigravity'.

Green-triangle line: reverse cumulative average of x(horiz.) annihilations (data)

Summary of Gravity Results

- The ALPHA trap has been used for gravity mearements using a new methodology that exploits single atom time-space resolution and simulations.
 - Simulate 10^6 antihydrogen simulations at many values of $F=M_G/M$.
 - Find the CDF for each F .
 - Use a Kolomogorov-Smirnov like statistic to measure the likelihood that the data could be from the simulated data distribution for a specific F .
- We can reject $F>110$ and $F<-65$ (including worst case systematic errors and statistical errors) at a significance level of 5%.

Future: Cold antihydrogen & gravity on ALPHA-II



Cold antihydrogen simulations $\langle y | t \rangle$: **Red** M_G/M=0; **Magenta** M_G/M=1; **Green** M_G/M=-1

Black Line: Fraction lost from trap Grey bands: 90% confidence interval for 500 annihilations.

Dark Yellow: cosmic S/N>5 for current trapping rates.

Light Yellow: cosmic S/N > 5 for x10 trapping rates.



ALPHA-II Overview

- Modular design: separate antiproton catching region from the “atomic physics” section. Access for multiple lasers; buildup cavity *in vacuo*
- Capable of accumulating antiprotons when available; using them when needed – possible 24 hour operation with pbars even before ELENA
- Catching trap (commissioned 2012) might feed two devices – horizontal & vertical?
- Magnets again from BNL – octupole, five mirror coils, and two solenoids
- Multiple mirror coils for Hbar manipulation, field tailoring & rapid charging solenoid for microwave exps
- Operation requires antiproton stacking and transport between catching and mixing traps
 - x10 or more increase in trapping requires higher antiproton flux, colder plasmas, better mixing
- Precision physics requires understanding of systematics
 - Novel experimental techniques exploit accelerator concepts and nonlinear dynamics
 - Precision physics campaign for 5+ years from CERN turn-on in 2014



ALPHA-2 : separation of functions

Cryo-free solenoid

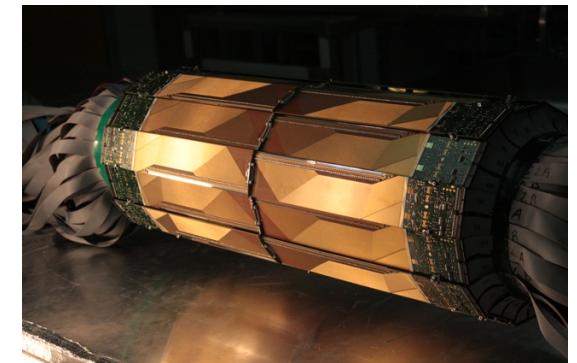


Liquid helium cooled solenoid
Oxford Instruments – financed by Carlsberg!

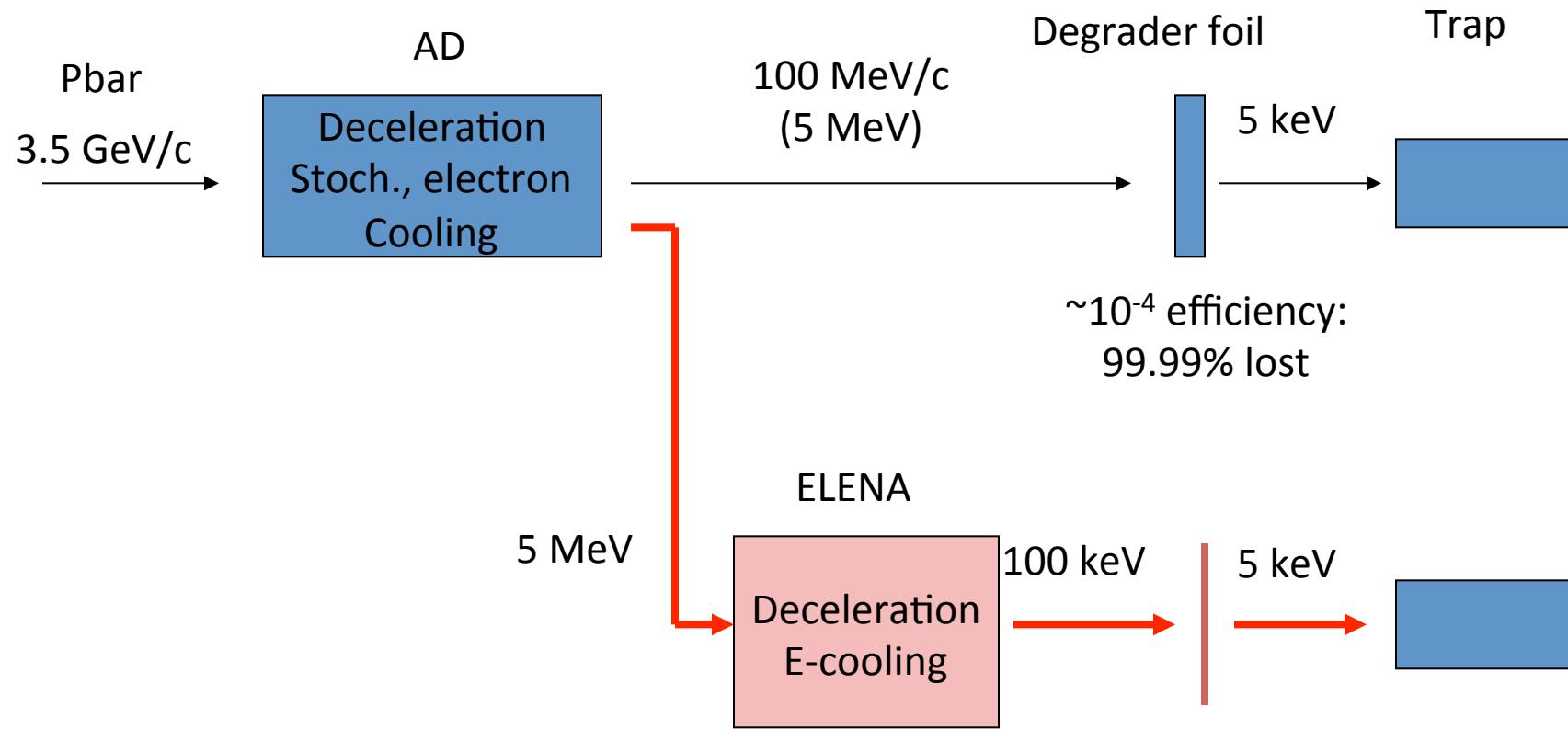


access
for lasers and microwaves

Positron accumulation



Cern builds an enhanced antiproton source: ELENA (completion ~ 2017)

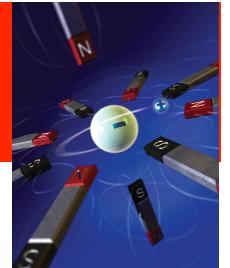


ELENA will provide ultra-low energy phase-space compressed beam enhancing number of usable antiprotons by x100 or more. We need to understand how best to use them.



ALPHA-II will open a new area of physics:

Neutral antimatter science



1. ALPHA-II is under development, with installation and characterization 2014 or 2015 (LHC shutdown fixes schedule).
2. Advantages associated with ability to measure each antihydrogen will be exploited. Incorporates many lessons learned on ALPHA.
3. Physics enhancements: laser access, separated catching and mixing traps, improved diagnostics, enhanced detector, stacking antiprotons antihydrogen, low noise (electrical and mechanical).
4. Physics Studies 2015-2020:
 - CPT: $1S \rightarrow 2S$ and microwave spectroscopy (frequency resolution <tens kHz)
 - gravity ($|M_g/M| \sim 1?$)

ALPHA Papers and information:

<http://alpha.web.cern.ch>

Movies/graphics:

raman.physics.berkeley.edu/gallery.html

